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Quartz Crystal Oscillator Vibration Measurements

Mark Berry, Todd Turner, and William McIntosh

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Army Research Laboratory

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Abstract

The U.S. Army Research Laboratory (ARL), specifically the RF Electronics Division of the Sensors and Electron Devices Directorate, has been tasked to become the Department of Defense (DoD) center for frequency control. As part of this program, ARL and others will develop frequency oscillators to be used as system clocks in munitions and other devices. ARL has assembled a test facility to measure the effects of vibration on frequency oscillators. This report discusses the results of vibration experiments on two quartz crystal oscillators, including verification of the measurement system and experimental setup.

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1. Introduction

The U.S. Army Research Laboratory (ARL), specifically the Radio Frequency (RF) Electronics Division of the Sensors and Electron Devices Directorate, has been tasked to become the Department of Defense (DoD) center for frequency control. As part of this program, ARL and others will develop frequency oscillators to be used as system clocks in munitions and other devices. A joint effort headed by the Composite and Lightweight Structures Branch with assistance from the Directed Energy Effects and Hardening Mitigation Branch (both of ARL) has led to the development of a facility to test acceleration effects on quartz crystal oscillators. Vibration experiments were conducted on two quartz crystal oscillators to verify the measurement setup. The theory behind this program is based on the paper "The Acceleration Sensitivity of Quartz Crystal Oscillators: A Review" by Raymond L. Filler.[1] This report discusses the effects of acceleration caused by vibration on the functioning of crystal oscillators. The effects of both single frequency and random vibrations on crystals are discussed. This report also discusses experimental setup and measurement techniques. The goal of this frequency control program is to determine if ARL can conduct vibration experiments and measure the effects of the vibration on crystals.

[1]Raymond L. Filler, "The Acceleration Sensitivity of Quartz Crystal Oscillators: A Review," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **35**, No. 3, May 1988.

2. Theory

As discussed in Filler's paper,[1] an oscillating crystal that is subjected to vibration will produce signals (sidebands) in addition to the original oscillating frequency (carrier). These sideband frequencies are related in location and amplitude to the vibration frequency and amplitude. If the vibration is a single frequency, the first sideband frequency that is produced will be seen at a frequency above and below the carrier frequency at a spacing that is equal to the frequency of vibration. The amplitude of the sideband (in decibel) is proportional to the amplitude of vibration and is related to the vibration sensitivity of the quartz crystal. The vibration sensitivity is a vector quantity that varies with respect to the plane of vibration. A oscillator should be measured in three (x, y, z) planes to obtain the vector direction and amplitude for the vibration sensitivity. According to Filler,[1] the frequency modulation index is calculated as

$$\beta = \frac{\Delta f}{f_V} , \tag{1}$$

where

$$\Delta f = f_0 \times A \times \gamma , \tag{2}$$

where f_0 is the crystal operating frequency, A is the acceleration in units of g-force (where g is the magnitude of the earth's gravitational acceleration of 9.80 m/s^2) of the vibration, and γ is the vibration sensitivity of the crystal. According to equation (15) of Filler's paper,[1] the loss difference L between the carrier frequency and the first sideband (signal f_v away) is equal to 20 log of 1/2 Δf over the vibration frequency or

$$L = 20 \times \log \left[\frac{(\gamma \times A \times f_0)}{(2 \times f_V} \right] . \tag{3}$$

This equation is also true for small values of β (i.e., $\Delta f << f_v$). Solving equation (3) for γ yields

$$\gamma = \left[\frac{\left(2 \times f_V \times \left(10^{\left(\frac{L}{20} \right)} \right) \right)}{(A \times f_0)} \right] . \tag{4}$$

As equation (4) shows, γ (the sensitivity per 1 g of acceleration) can be found from measurements of the vibration frequency, crystal oscillator frequency, the loss between the carrier and the sideband, and the amplitude of the vibration.

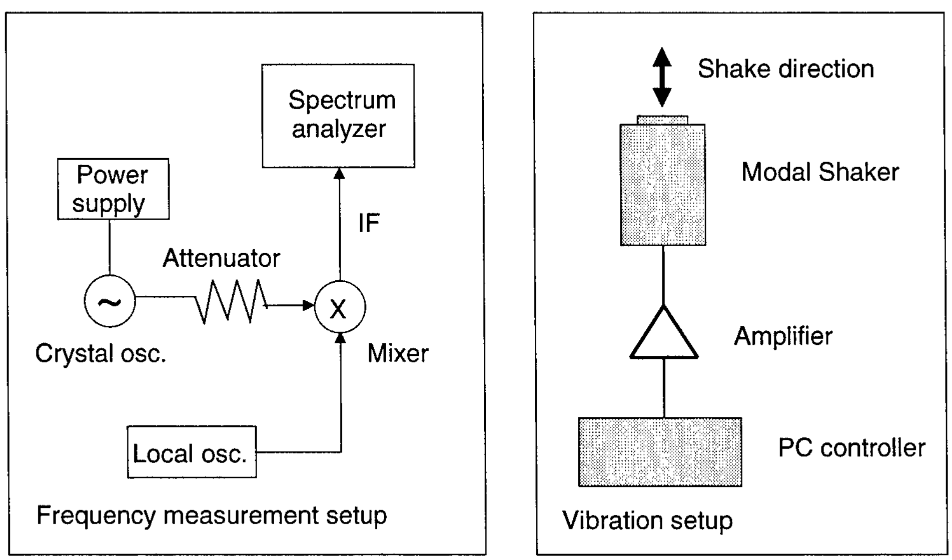
[1]Raymond L. Filler, "The Acceleration Sensitivity of Quartz Crystal Oscillators: A Review," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **35**, No. 3, May 1988.

3. Measurement Hardware

3.1 Crystal Oscillator Measurement Hardware

Accurate measurements are required to obtain the sensitivity to measure losses on the order of 80 dB on a spectrum analyzer (this is shown in Filler's paper in fig. 4 and table 1[1]). Some of the sidebands that he shows are 86 dB or more less than the carrier. If measurements were conducted at the crystal oscillator's operating frequency, then most spectrum analyzers in that frequency range would not have the sensitivity to measure small sidebands that are very close to the carrier. Measurements on the order of less than 1 Hz are required, where high-frequency spectrum analyzers can only measure video and resolution bandwidths to 10s of hertz minimum. The operating frequency of a crystal oscillator must be mixed with a local oscillator frequency (to examine the lower sideband signal) to an audio frequency so that the lower sideband and vibration frequency can be examined on an audio spectrum analyzer. The mixer used in these experiments was a Mini Circuits, Inc., ZAD-1 mixer. The measurement setup block diagram is shown in figure 1. Audio spectrum analyzers can obtain a video bandwidth and resolution bandwidth below 1 Hz. In these experiments, a Hewlett Packard (HP) 35650 Data Acquisition Front-End unit with an HP 35652A 50-kHz Input Module (audio frequencies up to 50 kHz) computer-controlled measurement analyzer was used in the frequency domain to obtain a resolution of less than 0.25 Hz. The resolution of less than 0.25 Hz allowed a lower sideband frequency of 10 kHz and a vibration frequency of 5 Hz (sideband) to be measured at the same time. Thirty-two averages were used to make

Figure 1. Experimental test setup



[1]Raymond L. Filler, "The Acceleration Sensitivity of Quartz Crystal Oscillators: A Review," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **35**, No. 3, May 1988.

the measurement. The local oscillator was a Marconi model 2022 signal generator, and the oscillator was powered by a dc power supply. A 47-μF bypass capacitor was connected across the power leads on the oscillator.

3.2 Test Fixture and Shaker Hardware

The two test devices were shaken with an MB Dynamics model PM75C-B Modal Shaker that was driven by an MB Dynamics model SS530 amplifier, which was controlled by a personal computer (PC). We measured the acceleration of the vibration with a model 7254A-100 accelerometer that was fed back into the controlling PC. The accelerometer was driven by a Piezotronic model 482A04 ICP (Integrated Circuit-Piezoelectric) power supply.

We attached the oscillator to the shaker by an aluminum fixture. The fixture was 2.531-in. wide × 2.531-in. long × 2.781-in. high. The fixture had a cutout at the top to hold the oscillator. The sides of the cutout were machined so that the oscillator could be press fit into the future to prevent side-to-side movement during the test. An aluminum bar was placed across the front to hold the oscillator tightly against the back wall, and another aluminum bar was placed across the top to prevent movement in the vertical, relative to the sides of the oscillator in the fixture. The fixture was held to the shaker table by four 8 to 32 cap screws. We cut two channels in the fixture to provide clearance for the two rows of pins on the oscillator and drilled four 7/8-in. holes 2 5/32-in. deep in the fixture to remove weight. The combined weight of the test fixture, the accelerometer, and the oscillator was 1.26 lb.

The relative position of the block and the oscillator was the same throughout the test. To test the fixture containing the oscillator, we rotated the fixture along each axis (x, y, z) and then placed an accelerometer on the fixture to capture the acceleration in the direction of vibration.

The maximum total table displacement (double amplitude or peak to peak) for the MB Shaker was 0.5 in. The frequency range was 5 to 10 kHz. The maximum allowable table acceleration in g's (A_{max}) per the instruction manual is given by

$$A_{\mathrm{max}} = \frac{F_r}{(W_{\mathrm{me}} + W_o)}, \tag{5}$$

where F_r is given as 75 lb; W_{me} is the weight (0.95 lb) of the moving table assembly; and W_o is the weight (1.26 lb) of the fixture, accelerometer, and the oscillator with the cables attached. Based on the capability of the shaker, the oscillator was subjected to the maximum acceleration (g) selected of 40 g. At a few of the frequencies, 40 g were not attainable (table 1).

[1]Raymond L. Filler, "The Acceleration Sensitivity of Quartz Crystal Oscillators: A Review," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **35**, No. 3, May 1988.

Table 1. Attainable vibration frequencies and resolvable signals.

Vibration frequency (Hz)	Acceleration (g)
5	0.31*
25	1, 5, 8*
50	1, 5, 10, 25, 31.9*
500	1, 5, 10, 25, 40†
1000	1, 5, 10, 25, 40†
2000	5, 10, 25, 40
3000	5, 10, 25, 40

*Maximum attainable by shaker.
†Signal not resolvable by spectrum analyzer.

4. Experiments

Two Vectron Laboratories, Inc., crystal oscillators (model CO-252F16) were measured under a series of vibration frequencies and amplitudes. Table 1 shows the matrix of parameters that were used in the experiments as well as the parameters that were either too high for the shaker or not resolvable by the spectrum analyzer. The oscillators operate at approximately 5 MHz (they can be adjusted plus or minus a few kilohertz). The past history of the oscillators was unknown, although they seemed to operate properly when we started the experiments. An aluminum fixture (described in sect. 3) was created to house the crystal oscillator and mount it to the shaker. The fixture, shaker, and crystal oscillator are shown in figure 2. Figure 3 shows a closeup of the oscillator and fixture mounted on the shaker, and figure 4 shows a sample measurement. As shown in the figure, the lower sideband (mixed down from the 5-MHz original crystal output) is shown at 10 kHz. In this case, the crystal oscillator was shaken at 50 Hz and 25 g. A signal at ±50 Hz from the lower sideband can be seen. The amplitude difference from the lower sideband to the first 50-Hz sideband is fed into equation (4) to obtain the vibration sensitivity. We conducted most of the experiments with a single frequency sine wave vibration, although we did attempt a random vibration experiment. Three orientations were used during the testing. The first was to have the screw on the oscillator facing upward (screw up). The second was to have the screw to the side of the oscillator (in relation to the vibration direction, which was up). The third was to have the oscillator horizontally mounted.

Figure 2. Shaker, mounting fixture, and oscillator.

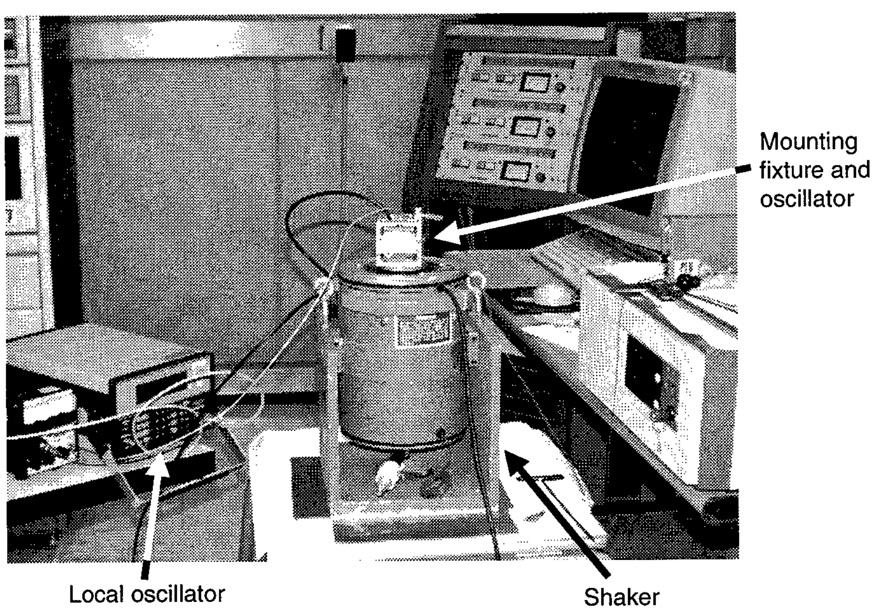


Figure 3. Shaker with oscillator and mount.

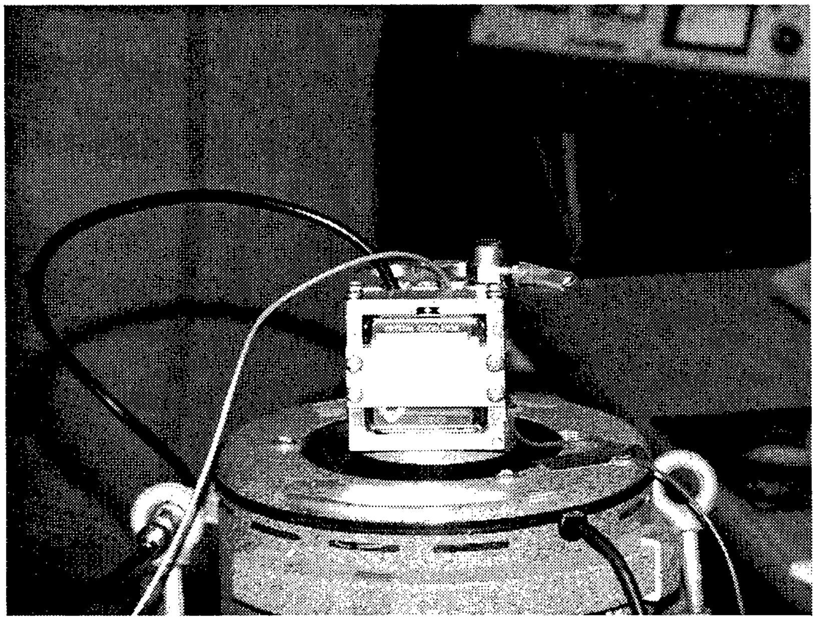
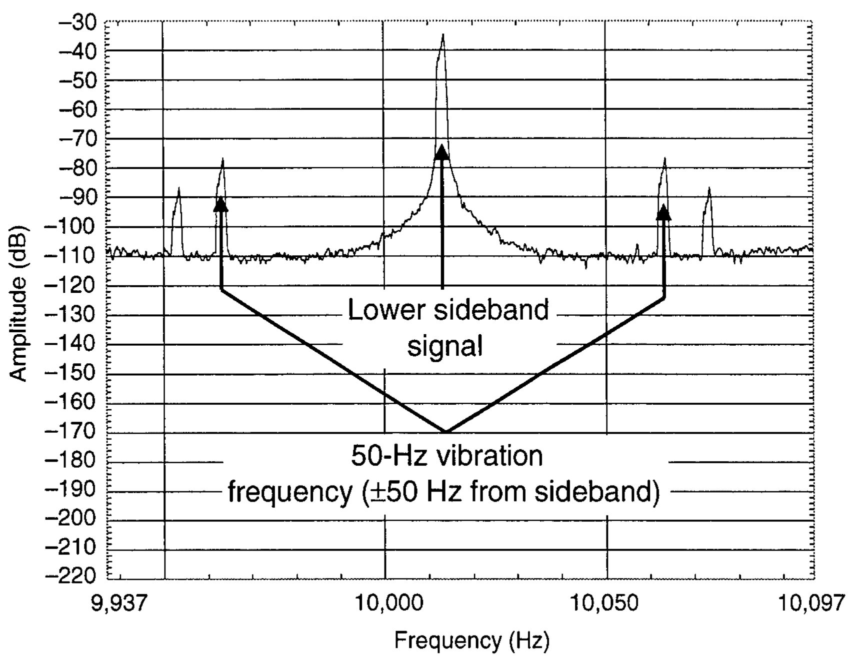


Figure 4. Sample vibration measurement (device 713896 at 50 Hz and 25 g).



4.1 Experimental Results

4.1.1 Single-Frequency Vibration

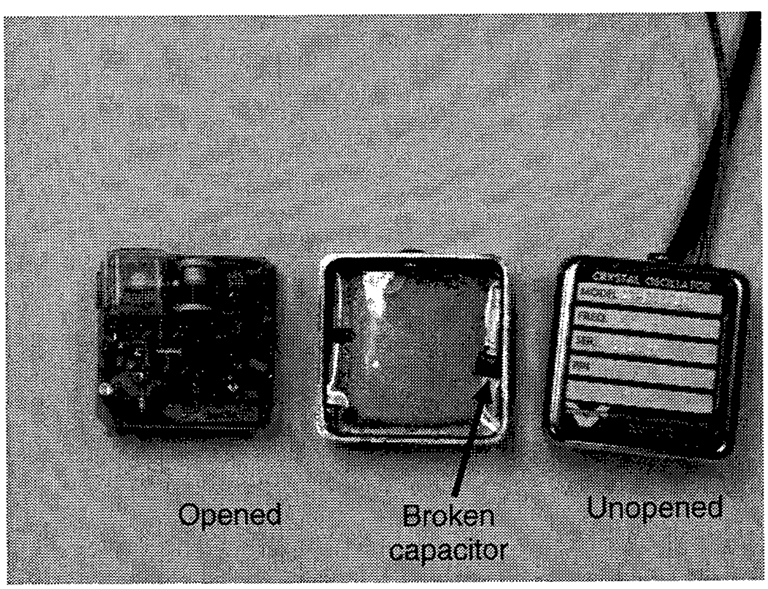
The complete shot record for the oscillator with serial number 713896 (also known as oscillator 96) is shown in appendix A, and the shot record for serial number 716774 (also knows as oscillator 74) is shown in appendix B. The corresponding frequency plot is called out in each appendix. All the frequency plots (figs. C-1 to C-131) are shown in appendix C. As shown in the data, several frequencies and vibration amplitudes were not resolvable on the spectrum output (shots 12, 25, 29, 33, 34, 49, 54, 59, 60, 77, 78, 95, 100,

121, 126, and 131). At some frequencies, the lower sideband frequency (with respect to the carrier) and sideband vibration frequencies were widened greatly. During these shots, a second tone was heard by the experimenters during the vibration (at 500 Hz and above, the shaker actually emitted a pure tone at the vibration frequency). We later found that there was a loose object in both oscillator cans, and the loose object was causing secondary oscillation effects (widening of the lower sideband and vibration frequencies) and audible tones. We noticed these secondary effects on shots 42, 43, 48, 67, 70, 71, 81, and 134. This loose object could have actually damaged the internal components of each oscillator and may have been responsible for some shifting of the carrier frequency during the vibration (although according to Filler,[1] a frequency shift is to be expected with an increase in acceleration or vibration amplitude). During the last shots on device 716774, the oscillator actually shifted permanently its oscillating frequency from 5.0 to 5.00535 MHz. The oscillator also became nonresponsive to adjustment of the trimmer, which would normally change the frequency of oscillation. We did not notice the loose object before the experiments began, so we assumed that it became loose as a result of the vibration testing. Device 716774 was cut open, and we found that a capacitor that was connected across the output of the crystal oscillator had broken loose from its solder joints. Also, several solder pieces were found loose in the can. Both crystals, the opened and unopened, are shown in figure 5.

4.1.2 Random Frequency Vibration

We conducted a random frequency vibration experiment on device 713896 using the waveform described in figure 6 of Filler's paper.[1] This vibration waveform was a typical aircraft random vibration envelope. To conduct

Figure 5. Crystal oscillator.



[1]Raymond L. Filler, "The Acceleration Sensitivity of Quartz Crystal Oscillators: A Review," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **35**, No. 3, May 1988.

these measurements, we required an analyzer with a dynamic range of 140 to 150 dB. The spectrum analyzer used for these experiments did not have adequate dynamic range to make the measurements in the experiments. Traces of the curve were barely seen, since they should have shown up at 70 dB below the carrier, but the noise floor could not be seen below 80 dB near the carrier.

We attempted to roughly estimate the random vibration measurement using the single vibration experiment data. The single vibration amplitudes were calculated from the aircraft vibration waveform in Filler's figure 6.[1] These amplitudes were 0.44, 1.0, 1.4, 5.9, 8.4, and 14.0 g for 5-, 25-, 50-, 500-, 1000-, and 2000-Hz vibration frequencies, respectively. The loss value for the closest vibration amplitudes were used in the calculation of γ at each f_v. The vibration amplitudes and loss values were not exact, so there could be substantial errors in the calculated γ numbers. Table 2 shows the calculated amplitudes and the amplitudes used in the calculation of γ. We calculated the $G(f)$ using Filler's equation (22)[1] for the different single frequency vibrations. The vibration sensitivity (γ) was calculated with Filler's equation (23), where the loss was taken from the single frequency vibration values. Solving for γ,

$$\gamma = \sqrt{\frac{\left(L \times \left(2 \times f_V^2\right)\right)}{\left(0.04 \times f_O^2\right)}}, \tag{6}$$

where L is the linear loss value. The calculated γ's settle in two ranges, 1 to 2×10^{-8} and 2 to 5×10^{-7}/g. These numbers were estimated from single vibration frequencies that were not exactly what the random amplitudes would have been, so there are errors in the calculated γ's. We had hoped that the γ's would not have ranged over an order of magnitude.

4.2 Vibration Sensitivities

As discussed in section 2, the vibration sensitivities (γ) were calculated from the spectrum analyzer results during the experiments. The vibration sensitivities seemed to track with the vibration frequency. The average vibration

Table 2. Calculated γ with use of random vibration amplitudes (calculated) and estimated vibration amplitudes (measured).

Vibration frequency (Hz)	Calculated amplitude (g)	Single-frequency amplitude (g)	Loss value (dB/linear)	Calculated γ (g)
5	0.44	0.31 (shot 35)	$57/2 \times 10^{-6}$	1×10^{-8}
25	1.00	1.0 (shot 36)	$65/3.2 \times 10^{-7}$	1.99×10^{-8}
50	1.40	1.0 (shot 39)	$70/1 \times 10^{-7}$	2.23×10^{-8}
500	5.90	10.0 (shot 46)	$68/1.6 \times 10^{-7}$	2.1×10^{-7}
1000	8.40	10.0 (shot 51)	$716774/4 \times 10^{-8}$	2.1×10^{-7}
2000	14.00	10.0 (shot 56)	$78/1.6 \times 10^{-8}$	5.4×10^{-7}

[1]Raymond L. Filler, "The Acceleration Sensitivity of Quartz Crystal Oscillators: A Review," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **35**, No. 3, May 1988.

sensitivities were calculated for each vibration frequency and are shown in table 3 for device 713896 and table 4 for device 716774. These numbers are calculated for the x (screw sideways), y (screw upward), and z (horizontal) directions, for device 713896. The numbers are calculated for the x and y directions for device 716774. Device 716774 was damaged before the experiments could be completed. Figure 6 shows the plot of the averages for each of the planes with device 713896. Figure 7 shows the plot of the averages for the two planes for device 716774. A vector can be calculated from the three components x, y, and z. The vector length l is calculated by

$$l = \sqrt{x^2 + y^2 + z^2} \ , \tag{7}$$

and the corresponding angles can be calculated with

$$\alpha = \cos^{-1} \times \left(\frac{x}{l} \right) . \tag{8}$$

The vector direction in relation to the device is shown in figure 8. The vector lengths for device 713896 have settled between 1.14 to 2.56×10^{-8}/g (within about a factor of two). This number is an order of magnitude above the vibration sensitivity as described by Filler,[1] although he describes the theory and not exact numbers for the particular crystals that were tested.

Table 3. Average vibration sensitivities for device 713896.

Vibration frequency (Hz)	Average gamma (/g)			Vector length (average)	Angle (radians)		
	Screw upward	Screw sideways	Horizontal		x-angle (α)	y-angle (β)	z-angle (γ)
5		9.41×10^{-9}	9.93×10^{-9}	1.36804×10^{-8}	—	—	—
25	2.31×10^{-8}	5.61×10^{-9}	9.61×10^{-9}	2.56405×10^{-8}	1.350217299	0.448913452	1.186617466
50	1.93×10^{-9}	5.64×10^{-9}	9.67×10^{-9}	1.13597×10^{-8}	1.051244909	1.400069709	0.552428157
500	1.48×10^{-8}	1.06×10^{-8}	9.37×10^{-9}	2.04743×10^{-8}	1.026609848	0.762867591	1.095449403
1000	1.88×10^{-8}	7.49×10^{-9}	9.90×10^{-9}	2.25289×10^{-8}	1.231883174	0.583599319	1.115825505
2000	6.43×10^{-9}	1.15×10^{-8}	1.58×10^{-8}	2.05727×10^{-8}	0.977624348	1.252919431	0.695069687
3000	9.56×10^{-9}	3.03×10^{-9}	1.80×10^{-8}	2.06052×10^{-8}	1.42321092	1.088335601	0.508315392

Table 4. Average vibration sensitivities for device 716774.

Vibration frequency (Hz)	Screw up	Screw sideways	Vector length (/g)	x angle (radians)	y angle (radians)
5	9.94×10^{-10}	1.18×10^{-9}	1.54287×10^{-9}	0.70004943	0.870746897
25	1.94×10^{-9}	2.23×10^{-9}	2.95576×10^{-9}	0.71596559	0.854830737
50	1.98×10^{-9}	1.70×10^{-9}	2.60967×10^{-9}	0.8613388	0.709457527
500	3.73×10^{-9}	3.08×10^{-9}	4.83728×10^{-9}	0.880557756	0.690238571
1000	2.07×10^{-8}	2.08×10^{-8}	2.9345×10^{-8}	0.78298853	0.787807797
2000	9.90×10^{-9}	—	9.9×10^{-9}	1.570796327	0
3000	1.57×10^{-7}	—	0.000000157	1.570796327	0

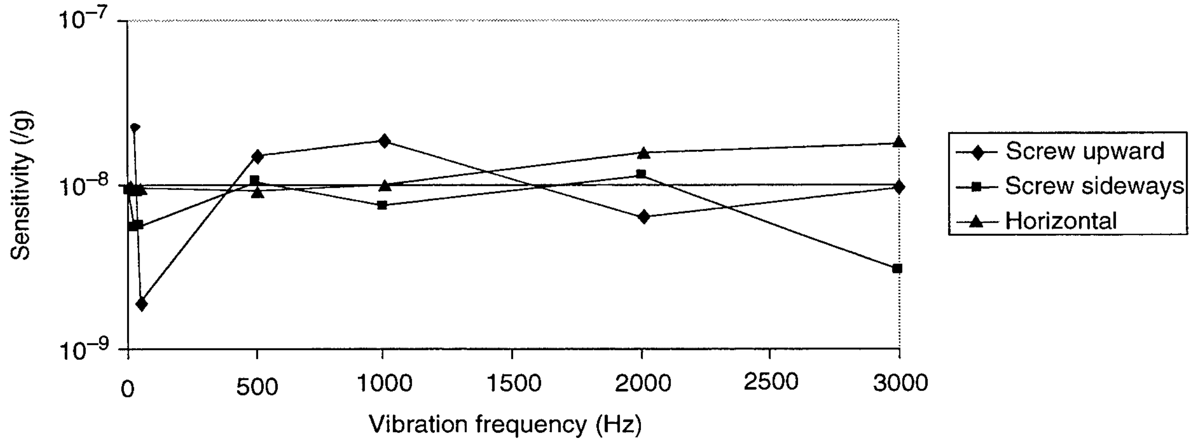


Figure 6. Average vibration sensitivity for device 713896.

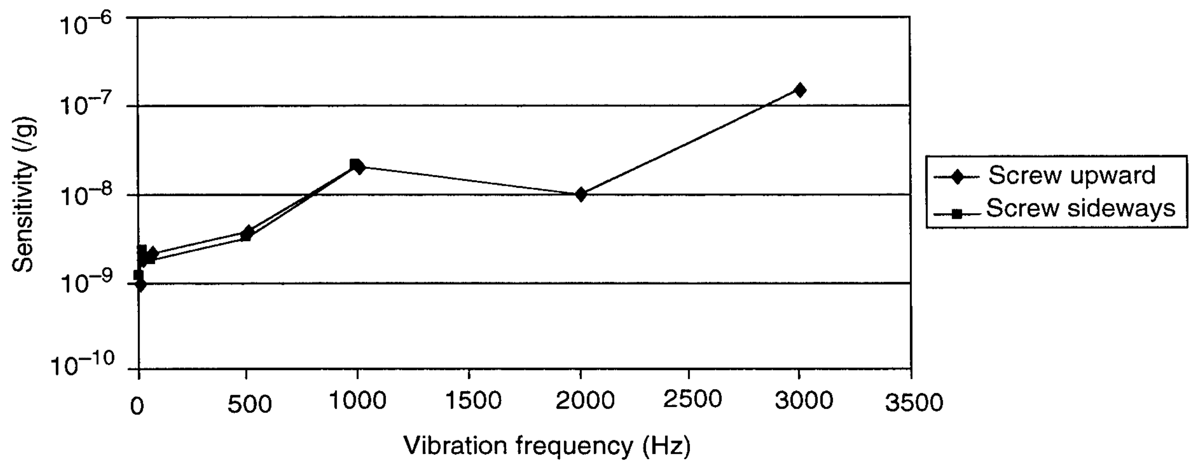
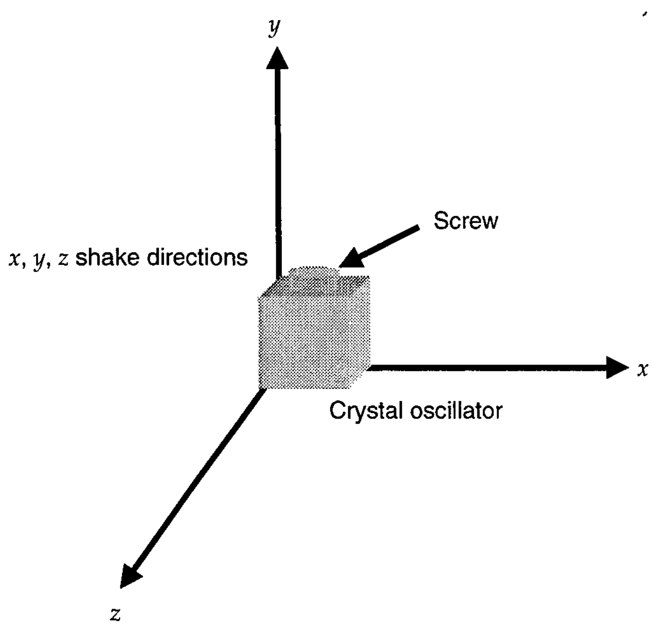


Figure 7. Average vibration sensitivity for device 716774.

Figure 8. Oscillator orientation and coordinate system.



5. Conclusions

We have shown that a reliable measurement setup can be constructed to determine the vibration sensitivities of a crystal under a variety of vibration parameters. The experimental methodology was verified as reliable and repeatable, although the dynamic range of the measurement system is less than desirable because of equipment limitations (especially in the random vibration experiments). In the future, as new crystals are developed, we are confident that ARL has the capabilities and expertise required to measure vibration sensitivities. Since the signal to noise of the measurement analyzer did not allow the measurement of the random vibration sidebands, we recommend that an audio amplifier be inserted between the mixer and the analyzer. This should decrease the noise figure of the measurement and possibly allow the noise floor to be dropped another 30 dB. A drop in 30 dB on the noise floor should provide at least a 100- to 120-dB dynamic range for the measurement and would allow the random vibration signal to be measured.

Appendix A. Shot Record for Oscillator 713896

Appendix A is a complete shot record for the oscillator with serial number 713896. The corresponding frequency plots are also listed. These plots are shown in appendix C as figures C-1 to C-84.

Shot number	Orientation	Vibration freq (Hz)	Amplitude (g)	dB difference	Gamma (calc) (/g)	Appendix C figure number	Comments
Baseline 1, 26 Sep 00		—	—			1	Oscillator at 10006 Hz. Shots 1–10 invalid (bad termination). 80-dB dyn range noise floor
10	Screw up	25	1	48	3.98×10^{-8}	2	–30 dB @ 10,008 Hz and –78 dB @ 10,033 Hz
11	Screw up	25	5	50	6.47×10^{-9}	3	–29 dB @ 10,008 Hz and –79 dB @ 10,033 Hz
12	Screw up	50	1	No signal	—	4	–29 dB @ 10,009 Hz, and no side lobe
13	Screw up	50	5	66	2.00×10^{-9}	5	–32 dB @ 10,009 Hz and –98 dB @ 10,059 Hz
14	Screw up	50	10	60	2.00×10^{-9}	6	–31 dB @ 10,009 Hz and –91 dB @ 10,059 Hz
15	Screw up	50	25	53	1.79×10^{-9}	7	–36 dB @ 10,012 Hz and –89 dB @ 10,062 Hz
16	Screw up	500	5	69	1.42×10^{-8}	8	–33 dB @ 10,017 Hz and –102 dB @ 10,517 Hz
17	Screw up	500	9	63	1.57×10^{-8}	9	–36 dB @ 10,017 Hz and –99 dB @ 10,517 Hz
18	Screw up	1000	5	70	2.53×10^{-8}	10	–39 dB @ 10,017 Hz and –70 dB @ 11,017 Hz
19	Screw up	500	10	63	1.41×10^{-8}	11	–38 dB @ 10,015 Hz and –63 dB @ 10,515 Hz
20	Screw up	500	25	54	1.60×10^{-8}	12	–38 dB @ 10,016 Hz and –92 dB @ 10,516 Hz
21	Screw up	500	40	51	1.41×10^{-8}	13	–39 dB @ 10,018 Hz and –90 dB @ 10,518 Hz
22	Screw up	1000	10	66	2.00×10^{-8}	14	–39 dB @ 10,032 Hz and –105 dB @ 11,032 Hz
23	Screw up	1000	25	60	1.59×10^{-8}	15	–39 dB @ 10,034 Hz and –98 dB @ 11,034 Hz
24	Screw up	1000	40	57	1.41×10^{-8}	16	–39 dB @ 10,032 Hz and –96 dB @ 11,034 Hz
Baseline 2, 26 Sep 00		—	—	—	—	17	10022 Hz (drift stayed) (unit left on for 2 hr, went back down to 10,022 from 10,032)
25	Screw up	2000	5	No signal	—	18	No signal
26	Screw up	2000	10	83	5.66×10^{-9}	19	–38 dB @ 10,021 Hz and –121 dB @ 12,021 Hz
27	Screw up	2000	25	72	8.03×10^{-9}	20	–39 dB @ 10,021 Hz and –111 dB @ 12,021 Hz
28	Screw up	2000	39.6	71	5.69×10^{-9}	21	–38 dB @ 10,023 Hz and –109 dB @ 12,023 Hz
29	Screw up	3000	5	No signal	—	22	No signal
30	Screw up	3000	10	83	8.49×10^{-9}	23	–38 dB @ 10,032 Hz and –121 dB @ 13,032 Hz
31	Screw up	3000	25	73	1.07×10^{-8}	24	–38 dB @ 10,034 Hz and –111 dB @ 13,034 Hz
32	Screw up	3000	40	70	9.48×10^{-9}	25	–38 dB @ 10,035 Hz and –108 dB @ 13,035 Hz
33	Screw up	—	10	No signal	—	None	Random vibration, signal changed slightly, noise floor came up, not resolvable
34	Screw up	—	15	No signal	—	None	Random vibration, signal changed slightly, still in the noise, not resolvable
Baseline 1, 27 Sep 00	—	—	—	—	—	26	10004 Hz (drift recovered overnight)
35	Screw to side	5	0.3	57	9.41×10^{-9}	27	–34 dB @ 10,010 Hz and –91 dB @ 10,015 Hz
36	Screw to side	25	1	65	5.62×10^{-9}	28	–32 dB @ 10,010 Hz and –97 dB @ 10,035 Hz
37	Screw to side	25	5	51	5.63×10^{-9}	29	–32 dB @ 10,011 Hz and –83 dB @ 10,036 Hz
38	Screw to side	25	8	47	5.58×10^{-9}	30	–33 dB @ 10,011 Hz and –80 dB @ 10,036 Hz
39	Screw to side	50	1	70	6.32×10^{-9}	31	–33 dB @ 10,011 Hz and –103 dB @ 10,061 Hz
40	Screw to side	50	5	58	5.03×10^{-9}	32	–33 dB @ 10,012 Hz and –91 dB @ 10,062 Hz
41	Screw to side	50	10	54	3.98×10^{-9}	33	–35 dB @ 10,012 Hz and –89 dB @ 10,062 Hz
42	Screw to side	50	25	41	7.13×10^{-9}	34	–35 dB @ 10,013 Hz and –76 dB @ 10,063 Hz

Shot number	Orientation	Vibration freq (Hz)	Amplitude (g)	dB difference	Gamma (calc) (/g)	Appendix C figure number	Comments
43	Screw to side	50	31.9	41	5.75×10^{-9}	35	–38 dB @ 10,017 Hz and –79 dB @ 10,067 Hz
44	Screw to side	500	1	79	2.24×10^{-8}	36	–38 dB @ 10,031 Hz and –117 dB @ 10,531 Hz, may have been in noise floor
45	Screw to side	500	5	71	1.13×10^{-8}	37	–36 dB @ 10,030 Hz and –107 dB @ 10,530 Hz, may have been in noise floor
46	Screw to side	500	10	68	7.96×10^{-9}	38	–33 dB @ 10,028 Hz and –101 dB @ 10,528 Hz
47	Screw to side	500	25	62	6.35×10^{-9}	39	–35 dB @ 10,026 Hz and –97 dB @ 10,526 Hz
48	Screw to side	500	40	60	4.99×10^{-9}	40	–40 dB @ 10,031 Hz and –100 dB @ 10,531 Hz
Baseline 2, 27 Sep 00	—	—	—	—	—	41	–39 dB @ 10,025 Hz (drift did not recover)
49	Screw to side	1000	1	No signal	—	42	–38 dB @ 10,025 Hz, not resolvable
50	Screw to side	1000	5	80	7.99×10^{-9}	43	–38 dB @ 10,024 Hz and –118 dB @ 11,024 Hz
51	Screw to side	1000	10	74	7.98×10^{-9}	44	–38 dB @ 10,025 Hz and –112 dB @ 11,025 Hz
52	Screw to side	1000	25	65	8.99×10^{-9}	45	–39 dB @ 10,025 Hz and –104 dB @ 11,025 Hz
53	Screw to side	1000	40	66	5.01×10^{-9}	46	–39 dB @ 10,028 Hz and –105 dB @ 11,028 Hz
54	Screw to side	2000	1	No signal	—	47	–41 dB @ 10,033 Hz, not resolvable
55	Screw to side	2000	5	84	1.01×10^{-8}	48	–39 dB @ 10,040 Hz and –123 dB @ 12,040 Hz
56	Screw to side	2000	10	78	1.01×10^{-8}	49	–39 dB @ 10,043 Hz and –117 dB @ 12,043 Hz
57	Screw to side	2000	25	69	1.13×10^{-8}	50	–39 dB @ 10,043 Hz and –108 dB @ 12,043 Hz
58	Screw to side	2000	39.4	63	1.44×10^{-8}	51	–38 dB @ 10,043 Hz and –101 dB @ 12,043 Hz
59	Screw to side	3000	5	No signal	—	52	–40 dB @ 10,047 Hz, not resolvable
60	Screw to side	3000	10	No signal	—	53	Not resolvable
61	Screw to side	3000	25	85	2.70×10^{-9}	54	–38 dB @ 10,051 Hz and –123 dB @ 13,051 Hz
62	Screw to side	3000	40	79	3.36×10^{-9}	55	–38 dB @ 10,051 Hz and –117 dB @ 13,051 Hz
Baseline 1, 28 Sep 00	—	—	—	—	—	56	–33 dB @ 10,007 Hz (drift recovered overnight)
63	Horizontal	5	0.3	56	9.93×10^{-9}	57	–35 dB @ 10,007 Hz and –91 dB @ 10,012 Hz
64	Horizontal	25	1	60	1.00×10^{-8}	58	–31 dB @ 10,008 Hz and –91 dB @ 10,033 Hz
65	Horizontal	25	5	46	1.00×10^{-8}	59	–32 dB @ 10,008 Hz and –78 dB @ 10,032 Hz
66	Horizontal	25	8	43	8.85×10^{-9}	60	–33 dB @ 10,008 Hz and –76 dB @ 10,033 Hz
67	Horizontal	50	1	67	8.93×10^{-9}	61	–31 dB @ 10,009 Hz and –98 dB @ 10,059 Hz
68	Horizontal	50	5	67	1.26×10^{-8}	62	–33 dB @ 10,007 Hz and –83 dB @ 10,057 Hz
69	Horizontal	50	10	47	8.93×10^{-9}	63	–33 dB @ 10,007 Hz and –80 dB @ 10,057 Hz
70	Horizontal	50	25	38	1.00×10^{-8}	64	–36 dB @ 10,008 Hz and –74 dB @ 10,058 Hz
71	Horizontal	50	31.9	38	7.89×10^{-9}	65	–38 dB @ 10,014 Hz and –76 dB @ 10,064 Hz
72	Horizontal	500	1	78	2.52×10^{-8}	66	–39 dB @ 10,023 Hz and –117 dB @ 10,523 Hz
73	Horizontal	500	5	74	7.98×10^{-9}	67	–38 dB @ 10,026 Hz and –112 dB @ 10,526 Hz
74	Horizontal	500	10	71	5.63×10^{-9}	68	–38 dB @ 10,026 Hz and –109 dB @ 10,526 Hz
75	Horizontal	500	25	65	4.50×10^{-9}	69	–39 dB @ 10,025 Hz and –104 dB @ 10,525 Hz
76	Horizontal	500	40	63	3.54×10^{-9}	70	–38 dB @ 10,026 Hz and –101 dB @ 10526 Hz
77	Horizontal	1000	1	No signal	—	71	–40 dB @ 10,035 Hz, not resolvable
78	Horizontal	1000	5	No signal	—	72	–38 dB @ 10,040 Hz, not resolvable

Shot number	Orientation	Vibration freq (Hz)	Amplitude (g)	dB difference	Gamma (calc) (/g)	Appendix C figure number	Comments
79	Horizontal	1000	10	79	4.49×10^{-9}	73	–40 dB @ 10,035 Hz and –118 dB @ 11,040 Hz
80	Horizontal	1000	25	62	1.27×10^{-8}	74	–40 dB @ 10,043 Hz and –102 dB @ 11,043 Hz
81	Horizontal	1000	40	58	1.25×10^{-8}	75	–45 dB @ 10,054 Hz and –103 dB @ 11,054 Hz
82	Horizontal	2000	5	82	1.27×10^{-8}	76	–38 dB @ 10,054 Hz and –120 dB @ 12,054 Hz
83	Horizontal	2000	10	72	2.01×10^{-8}	77	–38 dB @ 10,055 Hz and –110 dB @ 12,055 Hz
84	Horizontal	2000	25	66	1.60×10^{-8}	78	–37 dB @ 10,054 Hz and –103 dB @ 12,054 Hz
85	Horizontal	2000	40	63	1.42×10^{-8}	79	–37 dB @ 10,054 Hz and –103 dB @ 12,054 Hz
86	Horizontal	3000	5	84	1.51×10^{-8}	80	–39 dB @ 10,059 Hz and –123 dB @ 13,059 Hz
87	Horizontal	3000	10	76	1.90×10^{-8}	81	–38 dB @ 10,063 Hz and –114 dB @ 13,063 Hz
88	Horizontal	3000	25	68	1.91×10^{-8}	82	–37 dB @ 10,063 Hz and –105 dB @ 13,063 Hz
89	Horizontal	3000	40	64	1.89×10^{-8}	83	–38 dB @ 10,062 Hz and –102 dB @ 13,062 Hz
90	Horizontal	50	25	38	1.01×10^{-8}	84	–39 dB @ 10,063 Hz and –77 dB @ 10,113 Hz, check against shot 70

Appendix B. Shot Record for Oscillator 716774

Appendix B is a complete shot record for the oscillator with serial number 716774. The corresponding frequency plots are also listed. These plots are shown in appendix C as figures C-85 to C-131.

Shot Number	Orientation	Vibration freq (Hz)	Amplitude (g)	dB difference	Gamma (calc) (/g)	Figure number	Comments
Baseline	Screw up	—	—	—	—	85	Oscillator mixed at signal 9996 Hz
91	Screw up	5	0.3	76	9.94×10^{-10}	86	–31 dB @ 9,996 Hz, –107 dB @ 10,001 Hz
92	Screw up	25	1	71	2.82×10^{-10}	87	–38 dB @ 9,997 Hz, –109 dB @ 10,022 Hz
93	Screw up	25	5	62	1.59×10^{-9}	88	–38 dB @ 9,996 Hz, –100 dB @ 10,021 Hz
94	Screw up	25	8	59	1.40×10^{-9}	89	–38 dB @ 9,996 Hz, –97 dB @ 10,021 Hz
95	Screw up	50	1	—	—	90	No signal
96	Screw up	50	5	68	4.49×10^{-9}	91	–39 dB @ 9,996 Hz, –107 dB @ 10,046 Hz
97	Screw up	50	10	63	1.42×10^{-9}	92	–39 dB @ 9,996 Hz, –103 dB @ 10,046 Hz
98	Screw up	50	25	58	1.01×10^{-9}	93	–38 dB @ 9,996 Hz, –96 dB @ 10,046 Hz
99	Screw up	50	32	56	9.94×10^{-10}	94	–37 dB @ 9,996 Hz, –93 dB @ 10,046 Hz
100	Screw up	500	1	—	—	95	No signal
101	Screw up	500	5	76	6.34×10^{-9}	96	–37 dB @ 9,996 Hz, –113 dB @ 10,496 Hz
102	Screw up	500	10	75	3.56×10^{-9}	97	–38 dB @ 9,996 Hz, –113 dB @ 10,496 Hz
103	Screw up	500	25	70	2.53×10^{-9}	98	–38 dB @ 9,996 Hz, –108 dB @ 10,496 Hz
104	Screw up	500	40	68	2.51×10^{-9}	99	–38 dB @ 9,981 Hz, –104 dB @ 10,481 Hz
105	Screw up	1000	5	73	1.79×10^{-8}	100	–38 dB @ 9,980 Hz, –111 dB @ 10,980 Hz
106	Screw up	1000	10	73	8.95×10^{-9}	101	–37 dB @ 9,981 Hz, –110 dB @ 10,981 Hz
107	Screw up	1000	25	60	1.60×10^{-8}	102	–37 dB @ 9,981 Hz, –97 dB @ 10,981 Hz
108	Screw up	1000	40	48	3.98×10^{-8}	103	–42 dB @ 10,014 Hz, –90 dB @ 11,014 Hz
109	Screw up	2000	5	85	9.00×10^{-9}	104	–38 dB @ 10,016 Hz, –123 dB @ 12,016 Hz
110	Screw up	2000	10	79	8.98×10^{-9}	105	–37 dB @ 10,017 Hz, –116 dB @ 12,017 Hz
111	Screw up	2000	25	68	1.27×10^{-8}	106	–37 dB @ 10,017 Hz, –105 dB @ 12,017 Hz
112	Screw up	2000	40	67	8.93×10^{-9}	107	–37 dB @ 11,016 Hz, –104 dB @ 12,016 Hz
113	Screw up	3000	5	63	—	108	No signal
114	Screw up	3000	10	55	2.13×10^{-7}	109	–37 dB @ 11,016 Hz, –92 dB @ 13,016 Hz
115	Screw up	3000	25	50	1.52×10^{-7}	110	–37 dB @ 10,015 Hz. –87 dB @ 13,015 Hz
116	Screw up	3000	40	50	9.49×10^{-8}	111	–37 dB @ 10,015 Hz, –87 dB @ 13,015 Hz
Baseline	Screw to side	—	—	—	—	112	–38 dB @ 10,018 Hz
117	Screw to side	5	0.3	75	1.18×10^{-9}	113	–31 dB @ 10,017 Hz, –106 dB @ 10,022 Hz
118	Screw to side	25	1	73	2.24×10^{-9}	114	–31 dB @ 10,017 Hz, –104 dB @ 10,042 Hz
119	Screw to side	25	5	59	2.24×10^{-9}	115	–32 dB @ 10,017 Hz, –91 dB @ 10,042 Hz
120	Screw to side	25	8	55	1.40×10^{-9}	116	–32 dB @ 10,017 Hz, –89 dB @ 10,042 Hz
121	Screw to side	50	1	—	—	117	No signal
122	Screw to side	50	5	68	1.59×10^{-9}	118	–32 dB @ 10,017 Hz, –100 dB @ 10,067 Hz
123	Screw to side	50	10	61	1.78×10^{-9}	119	–31 dB @ 10,017 Hz, –92 dB @ 10,067 Hz
124	Screw to side	50	25	53	1.79×10^{-9}	120	–31 dB @ 10,017 Hz, –84 dB @ 10,067 Hz

Shot Number	Orientation	Vibration freq (Hz)	Amplitude (g)	dB difference	Gamma (calc) (/g)	Figure number	Comments
125	Screw to side	50	31	52	1.63×10^{-9}	121	–31 dB @ 10,017 Hz, 83 dB @ 10,067 Hz
126	Screw to side	500	1	—	—	122	No signal
127	Screw to side	500	5	85	2.24×10^{-9}	123	–37 dB @ 10,017 Hz, –116 dB @ 10,517 Hz
128	Screw to side	500	10	69	1.12×10^{-9}	124	–38 dB @ 10,017 Hz, –107 dB @ 10,517 Hz
129	Screw to side	500	25	65	4.50×10^{-9}	125	–38 dB @ 9,974 Hz, –103 dB @ 10,474 Hz
130	Screw to side	500	40	61	4.46×10^{-9}	126	–37 dB @ 9,969 Hz, –98 dB @ 10,469 Hz
131	Screw to side	1000	1	—	—	127	No signal
132	Screw to side	1000	5	75	1.42×10^{-8}	128	–39 dB @ 9,968 Hz, –114 dB @ 10,968 Hz
133	Screw to side	1000	10	74	7.98×10^{-9}	129	–37 dB @ 9,968 Hz, –111 dB @ 10,968 Hz
134	Screw to side	1000	25	52	4.02×10^{-8}	130	–39 dB @ 10,008 Hz, –91 dB @ 1,108 Hz
135	Screw to side	1000	40	—	—	131	Crystal broken, frequency permanently shifted up to 5.00535 MHz

Appendix C. Shot Figures

This appendix gives the frequency plots (figs C-1 to C-131) for shot records listed in appendixes A and B of oscillators with serial numbers 713896 and 716774, respectively.

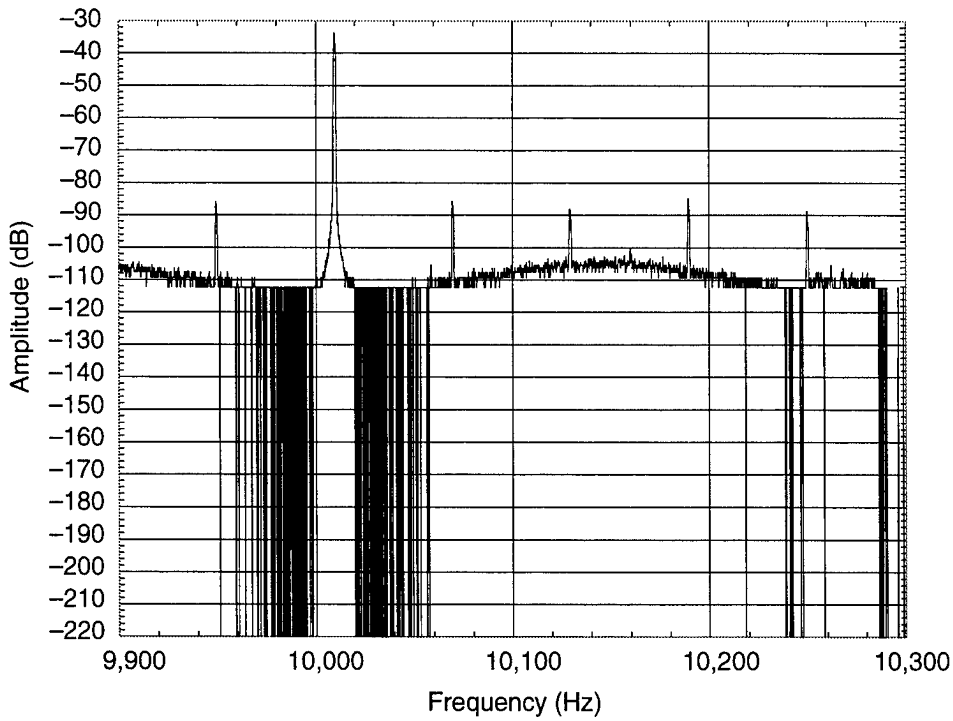


Figure C-1. Baseline measurement oscillator 96 screw up, vertical vibration.

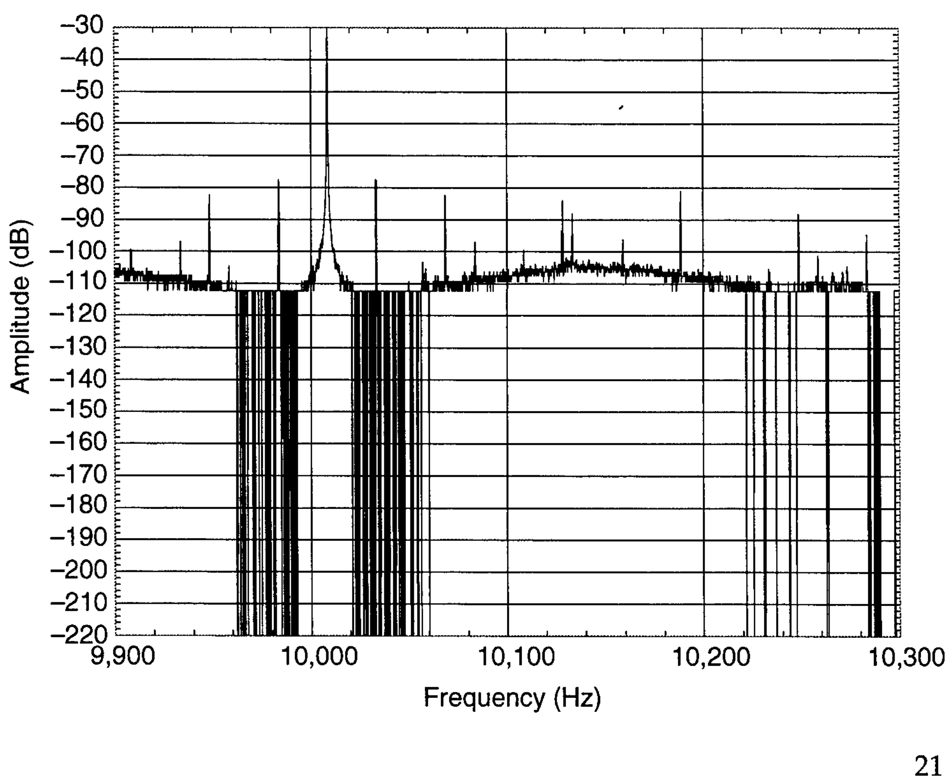


Figure C-2. Oscillator 96, 1 g at 25 Hz, screw up, vertical vibration, $\gamma = 3.98 \times 10^{-8}/g$.

Figure C-3. Oscillator 96, 5 g at 25 Hz, screw up, vertical vibration, $\gamma = 6.47 \times 10^{-9}/g$.

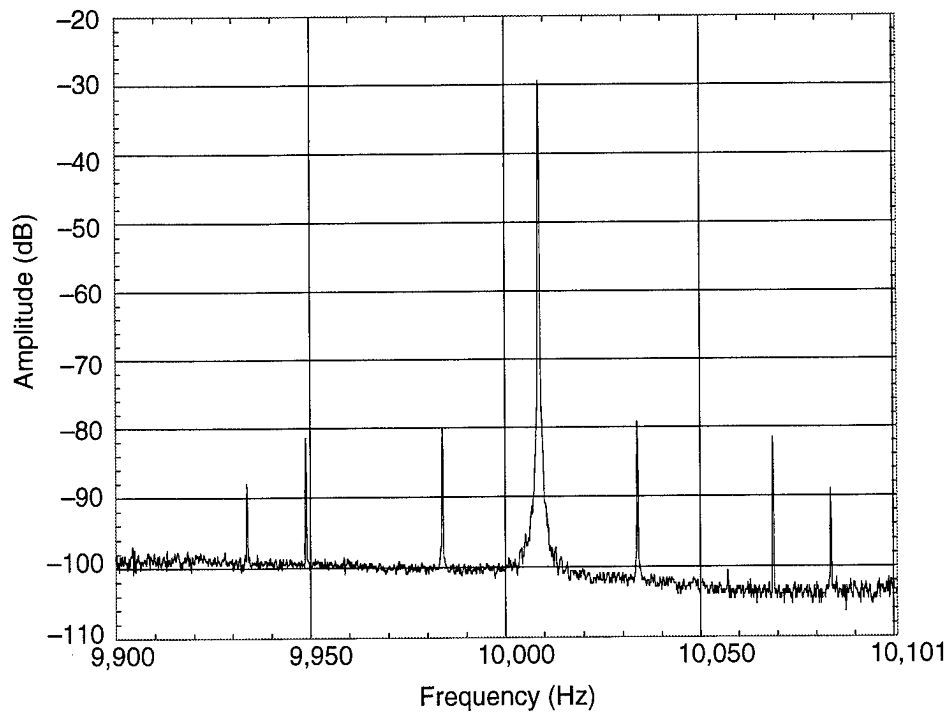


Figure C-4. Oscillator 96, 1 g at 50 Hz, screw up, vertical vibration.

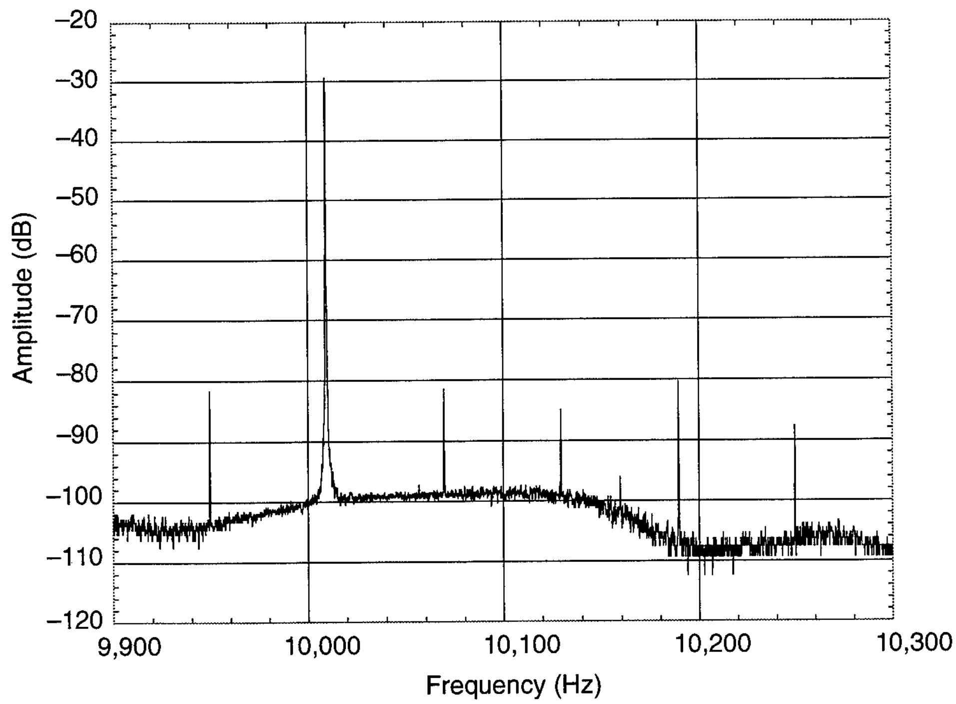


Figure C-5. Oscillator 96, 5 g at 50 Hz, screw up, vertical vibration, $\gamma = 2.00 \times 10^{-9}/g$.

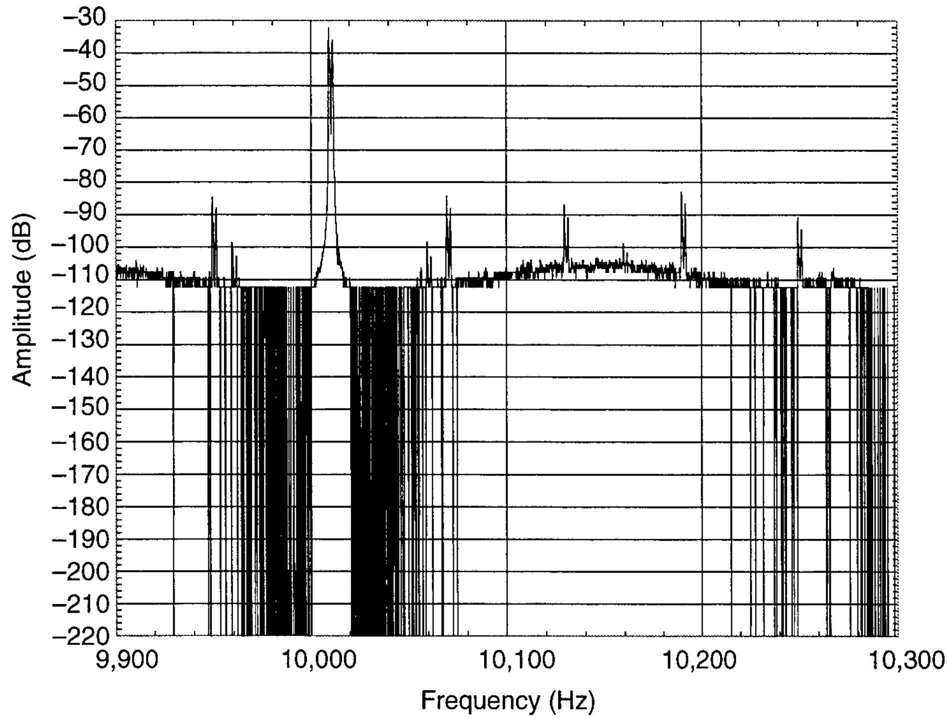


Figure C-6. Oscillator 96, 10 g at 50 Hz, screw up, vertical vibration, $\gamma = 2.00 \times 10^{-9}/g$.

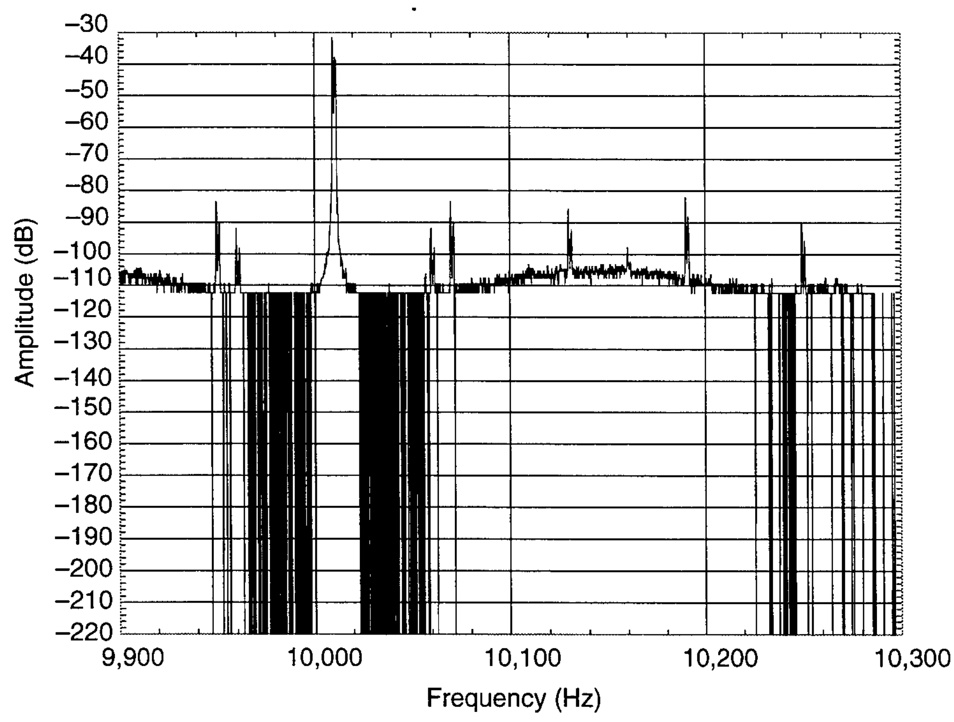


Figure C–7. Oscillator 96, 25 g at 50 Hz, screw up, vertical vibration, $\gamma = 1.79 \times 10^{-9}/g$.

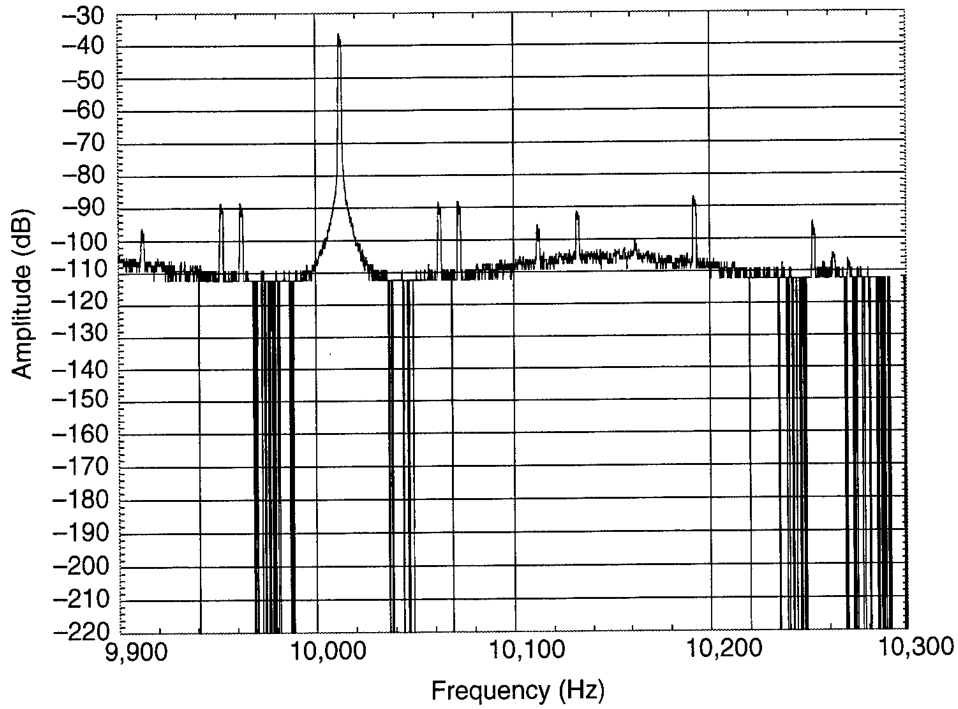


Figure C–8. Oscillator 96, 5 g at 500 Hz, screw up, vertical vibration, $\gamma = 1.42 \times 10^{-8}/g$.

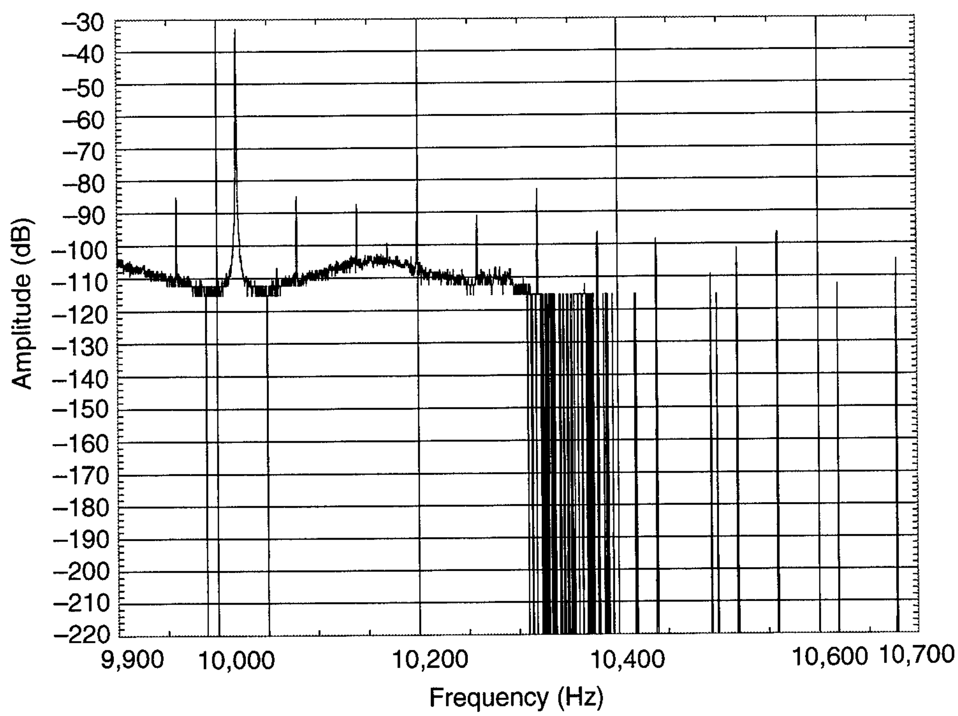


Figure C–9. Oscillator 96, 9 g at 500 Hz, screw up, vertical vibration, $\gamma = 1.57 \times 10^{-8}/g$.

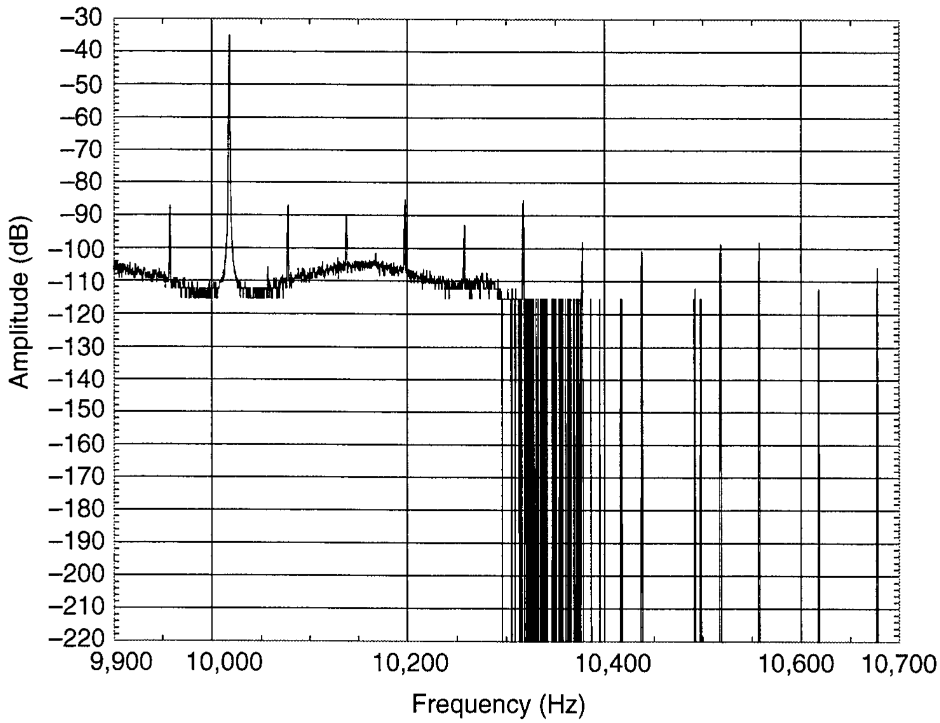
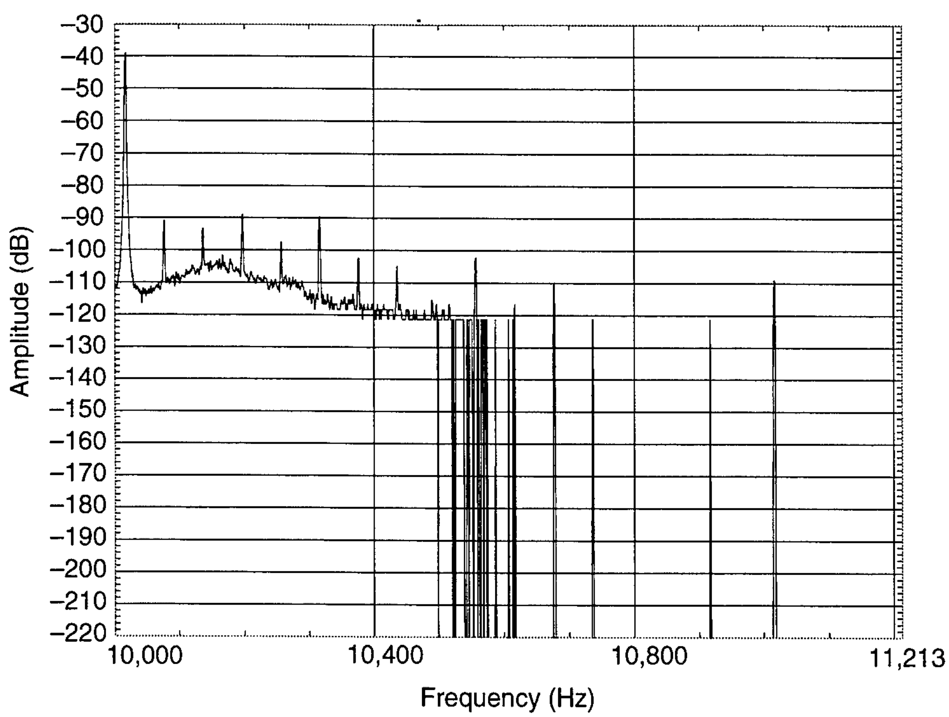


Figure C–10. Oscillator 96, 5 g at 1000 Hz, screw up, vertical vibration, $\gamma = 2.53 \times 10^{-8}/g$.



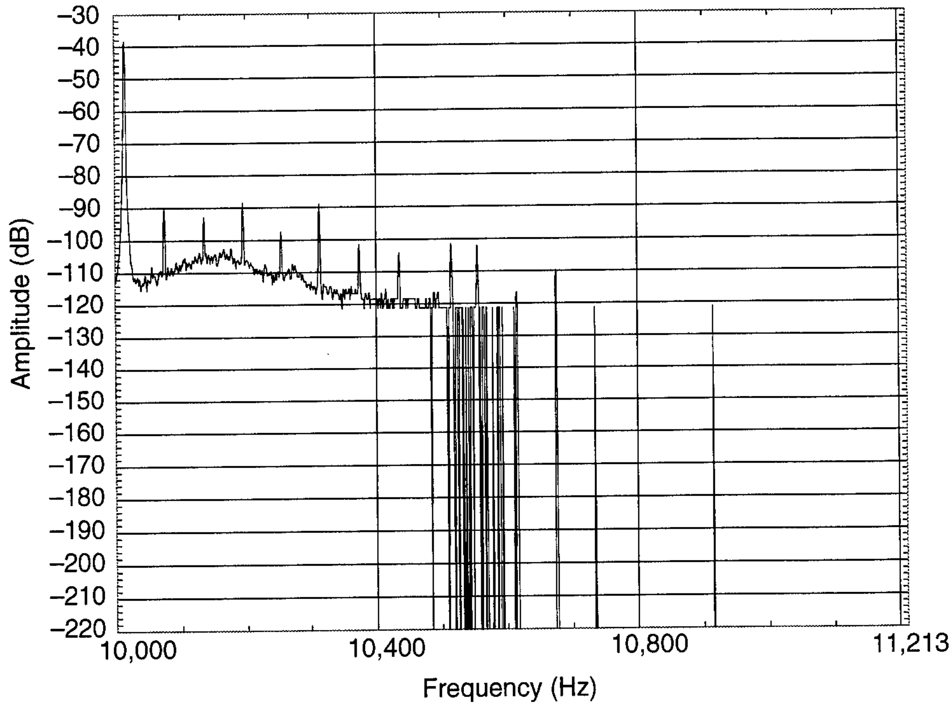


Figure C-11. Oscillator 96, 10 g at 500 Hz, screw up, vertical vibration, $\gamma = 1.41 \times 10^{-8}/g$.

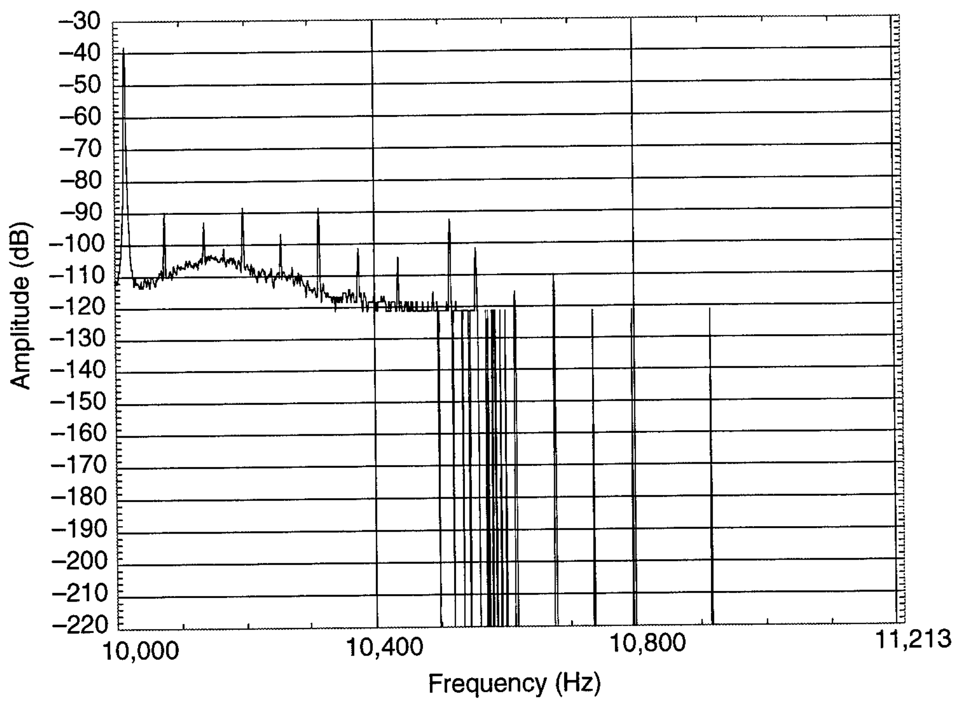


Figure C-12. Oscillator 96, 25 g at 500 Hz, screw up, vertical vibration, $\gamma = 1.60 \times 10^{-8}/g$.

Figure C-13. Oscillator 96, 40 g at 500 Hz, screw up, vertical vibration, $\gamma = 1.41 \times 10^{-8}/g$.

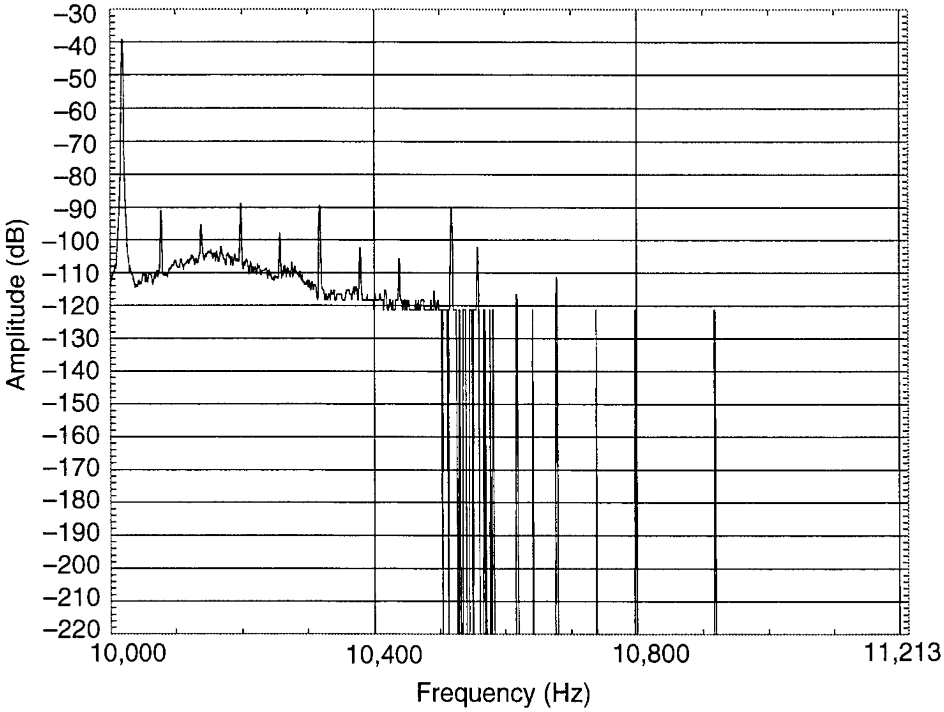


Figure C-14. Oscillator 96, 10 g at 1000 Hz, screw up, vertical vibration, $\gamma = 2.00 \times 10^{-8}/g$.

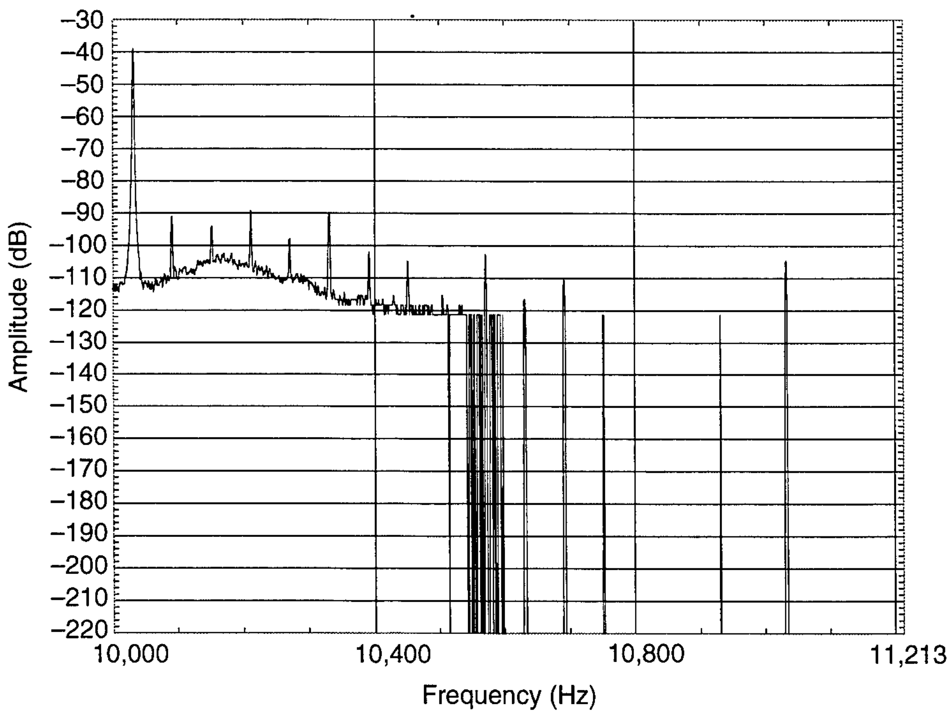


Figure C-15. Oscillator 96, 25 g at 1000 Hz, screw up, vertical vibration, $\gamma = 1.59 \times 10^{-8}/g$.

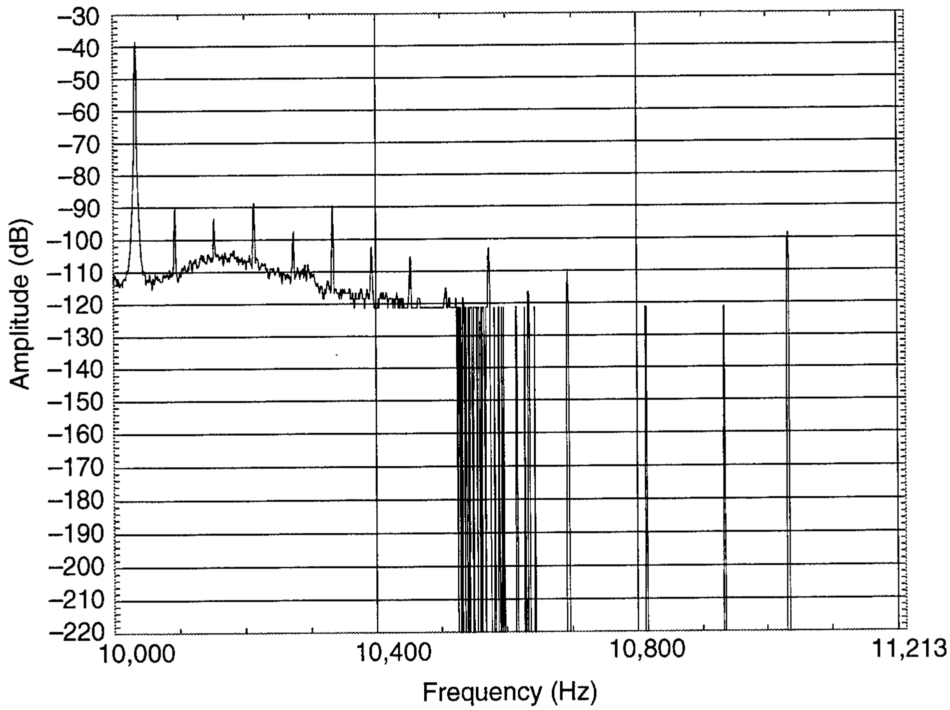


Figure C-16. Oscillator 96, 40 g at 1000 Hz, screw up, vertical vibration, $\gamma = 1.41 \times 10^{-8}/g$.

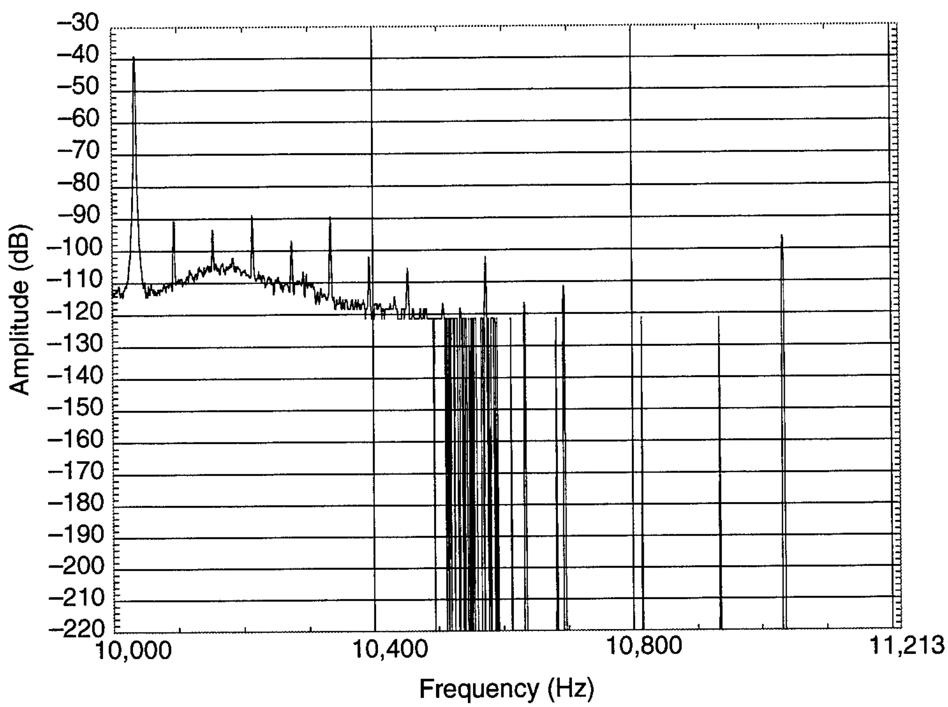


Figure C-17. Baseline 2 measurement oscillator 96 screw up, vertical vibration.

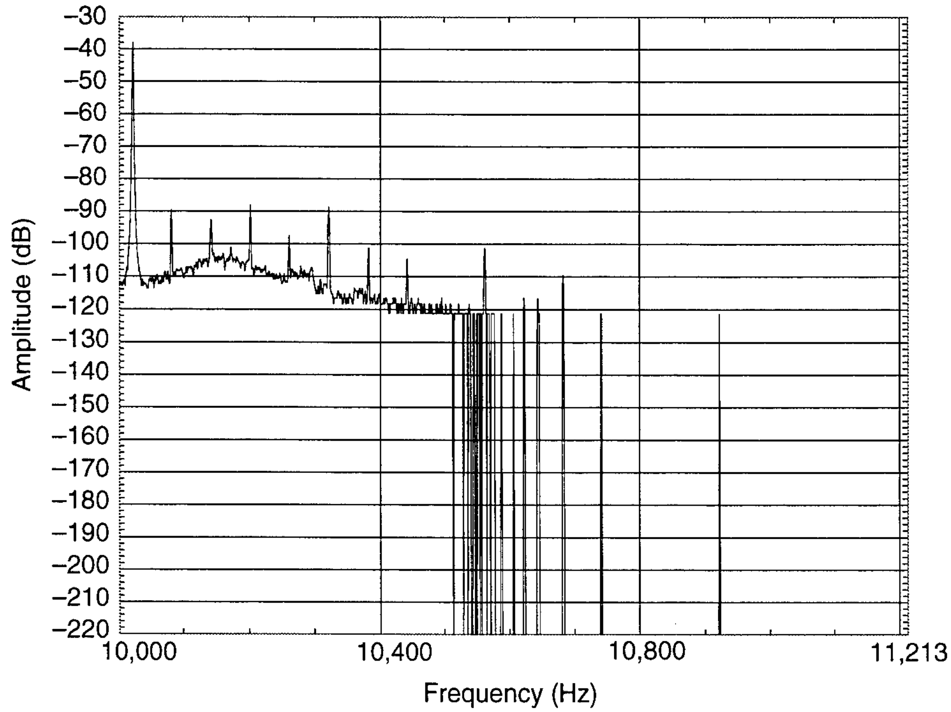


Figure C-18. Oscillator 96, 5 g at 2000 Hz, screw up, vertical vibration.

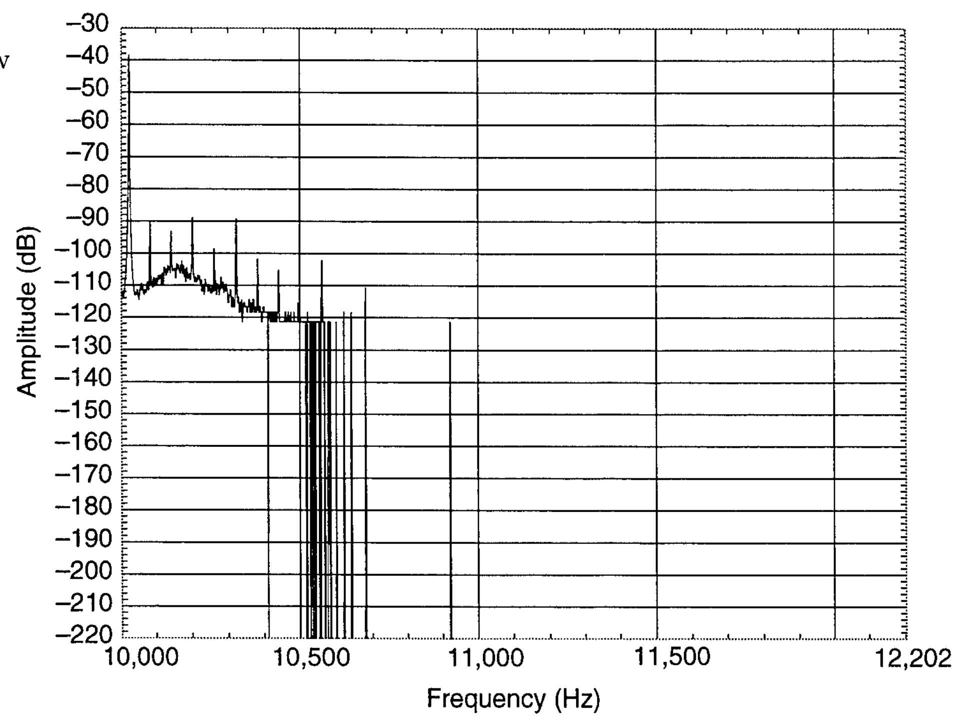


Figure C-19. Oscillator 96, 10 g at 2000 Hz, screw up, vertical vibration, $\gamma = 5.66 \times 10^{-9}/g$.

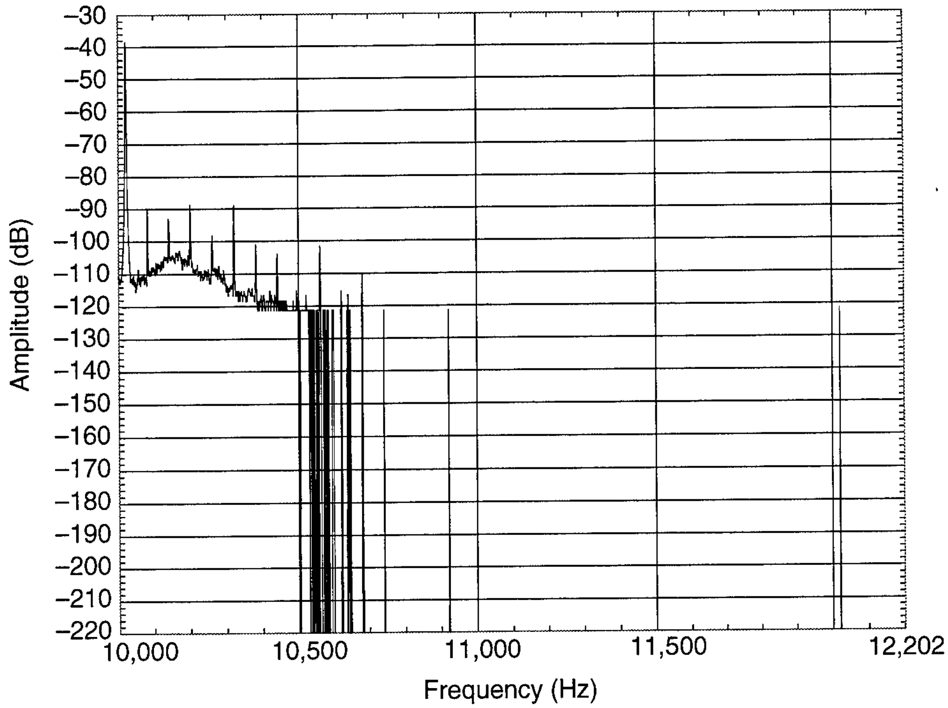


Figure C-20. Oscillator 96, 25 g at 2000 Hz, screw up, vertical vibration, $\gamma = 8.03 \times 10^{-9}/g$.

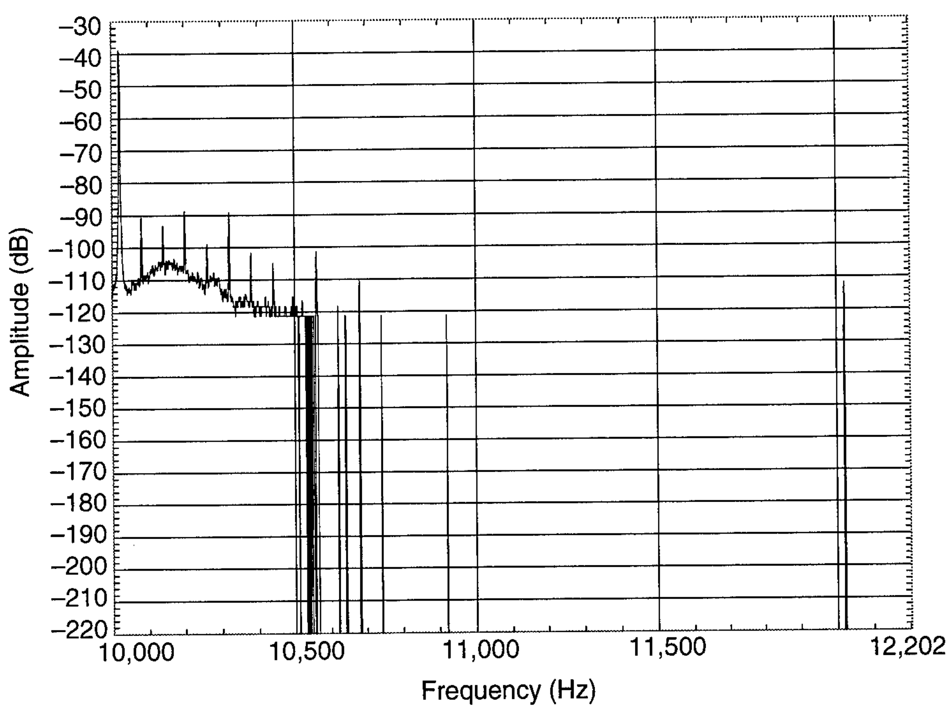


Figure C-21. Oscillator 96, 39.6 g at 2000 Hz, screw up, vertical vibration, $\gamma = 5.69 \times 10^{-9}/g$.

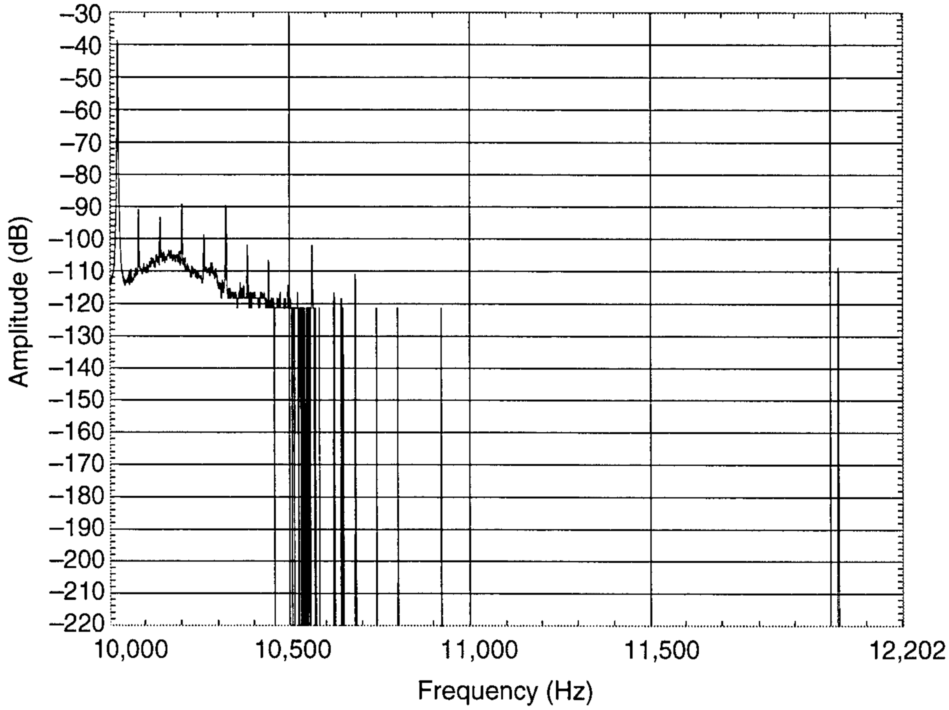


Figure C-22. Oscillator 96, 5 g at 3000 Hz, screw up, vertical vibration.

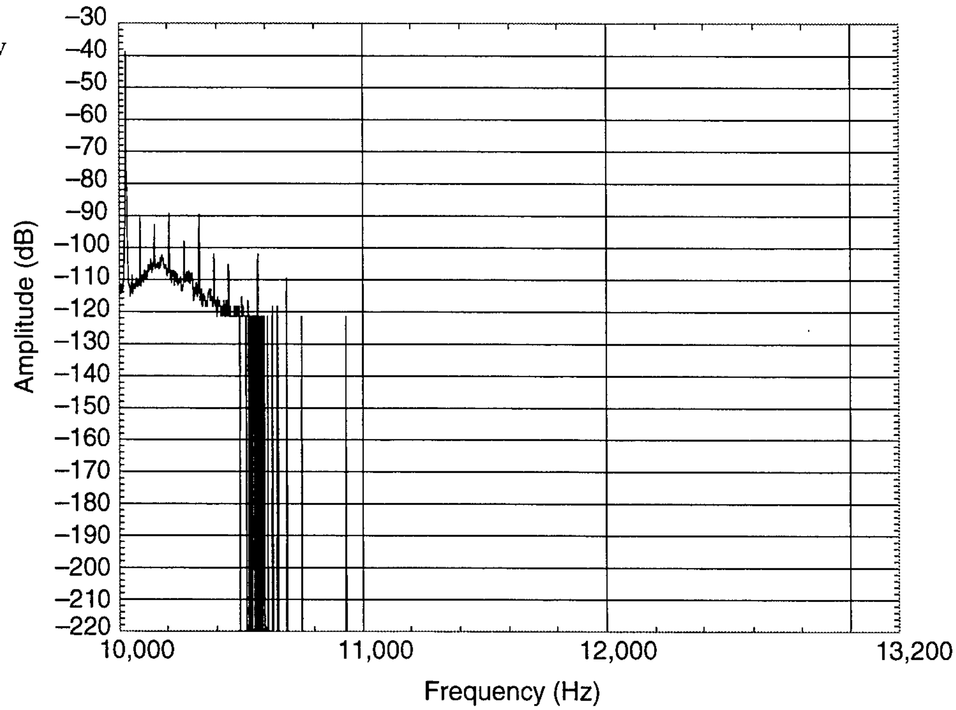


Figure C-23. Oscillator 96, 10 g at 3000 Hz, screw up, vertical vibration, $\gamma = 8.49 \times 10^{-9}$/g.

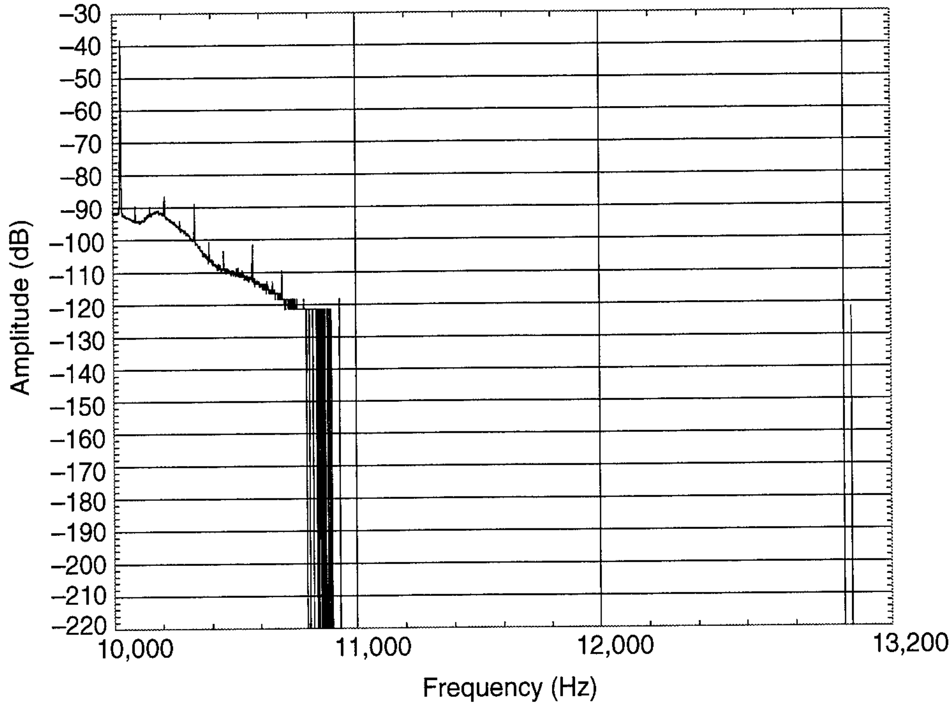
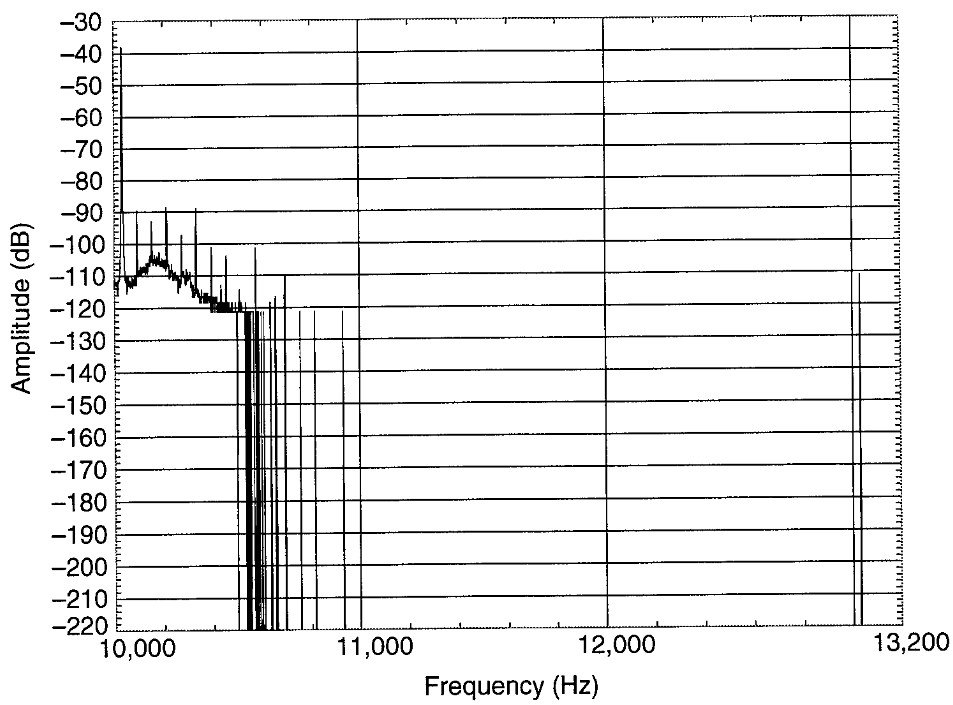


Figure C-24. Oscillator 96, 25 g at 3000 Hz, screw up, vertical vibration, $\gamma = 1.07 \times 10^{-8}$/g.



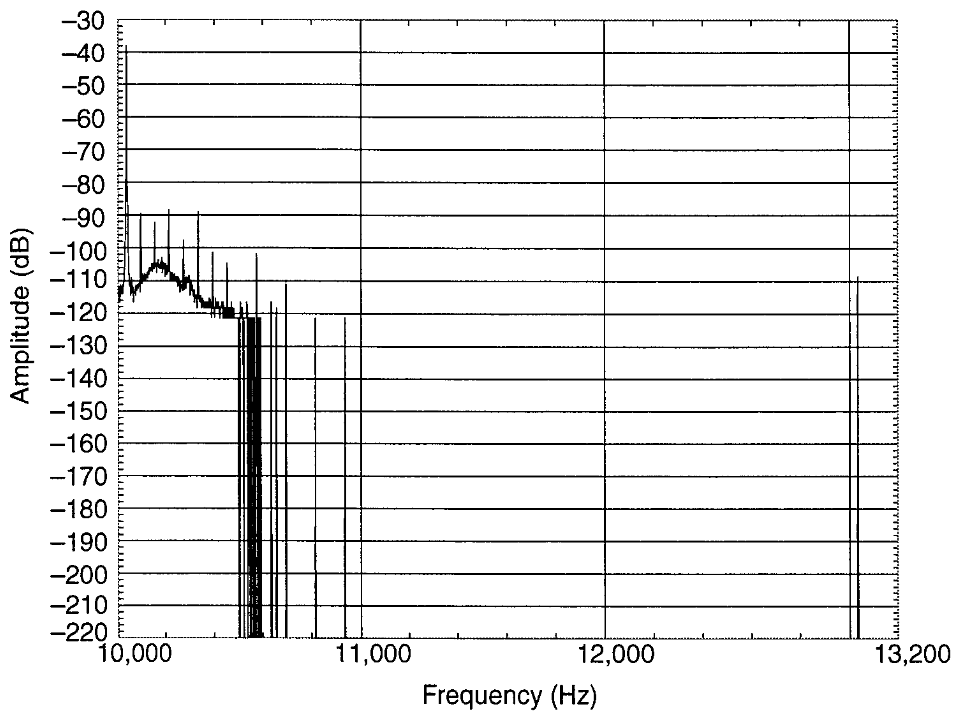


Figure C-25. Oscillator 96, 40 g at 3000 Hz, screw up, vertical vibration, $\gamma = 9.48 \times 10^{-9}$/g.

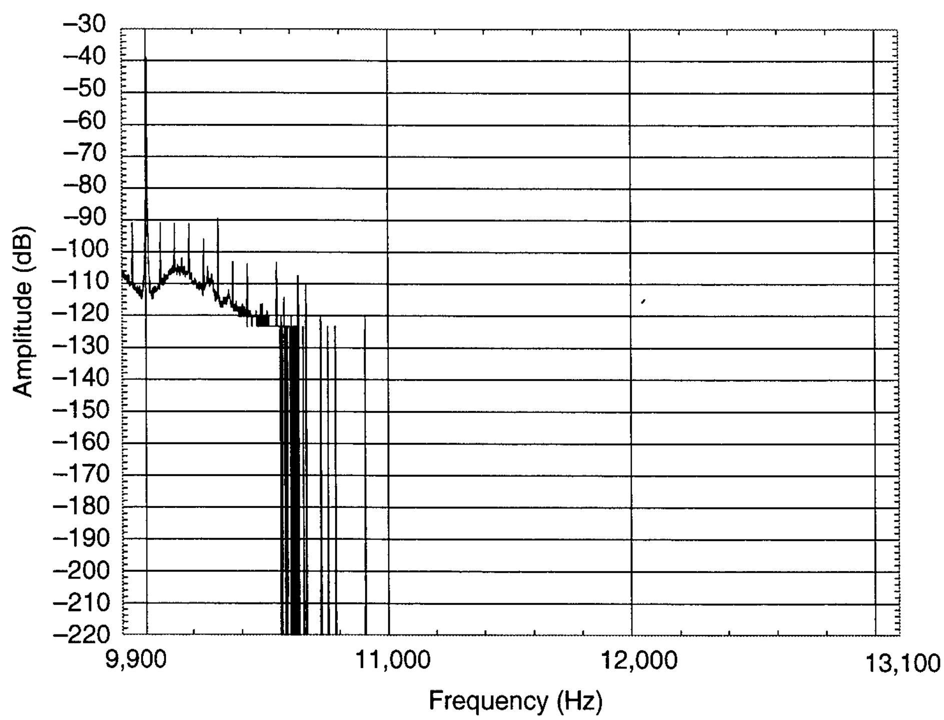


Figure C-26. Baseline 1 measurement oscillator 96 screw sideways, vertical vibration.

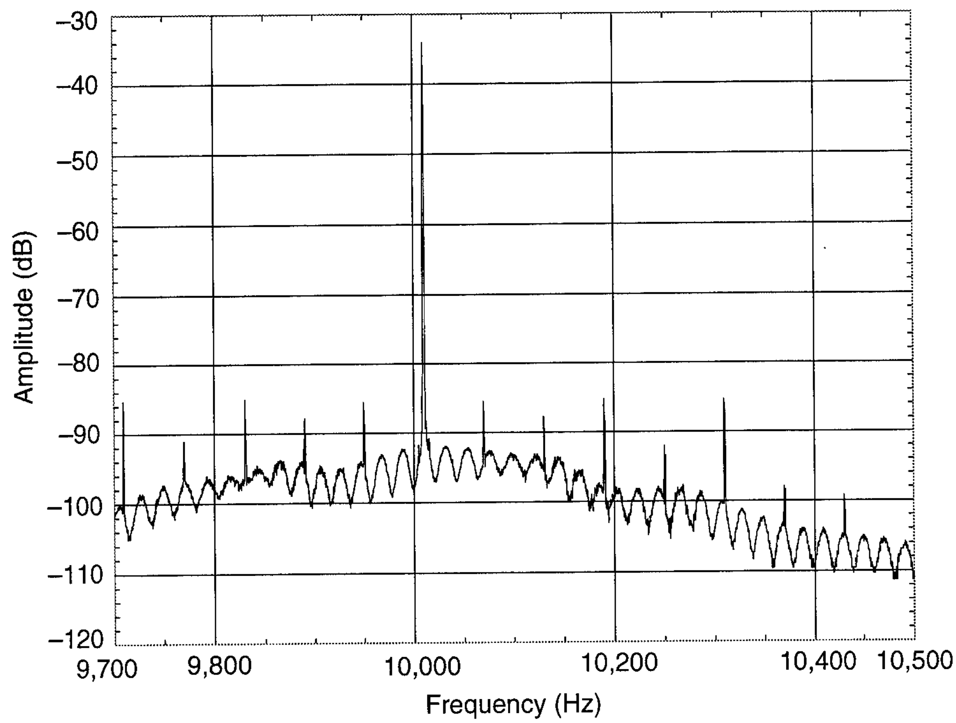


Figure C-27. Oscillator 96, .03 g at 5 Hz, screw sideways, vertical vibration, $\gamma = 9.41 \times 10^{-9}/g$.

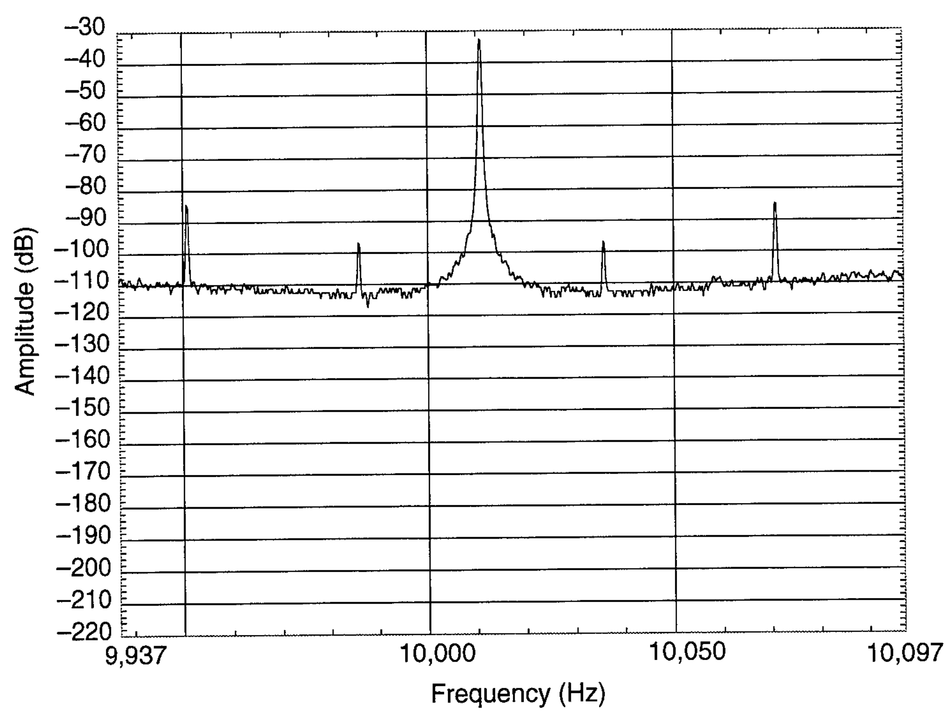


Figure C-28. Oscillator 96, 1 g at 25 Hz, screw sideways, vertical vibration, $\gamma = 5.62 \times 10^{-9}/g$.

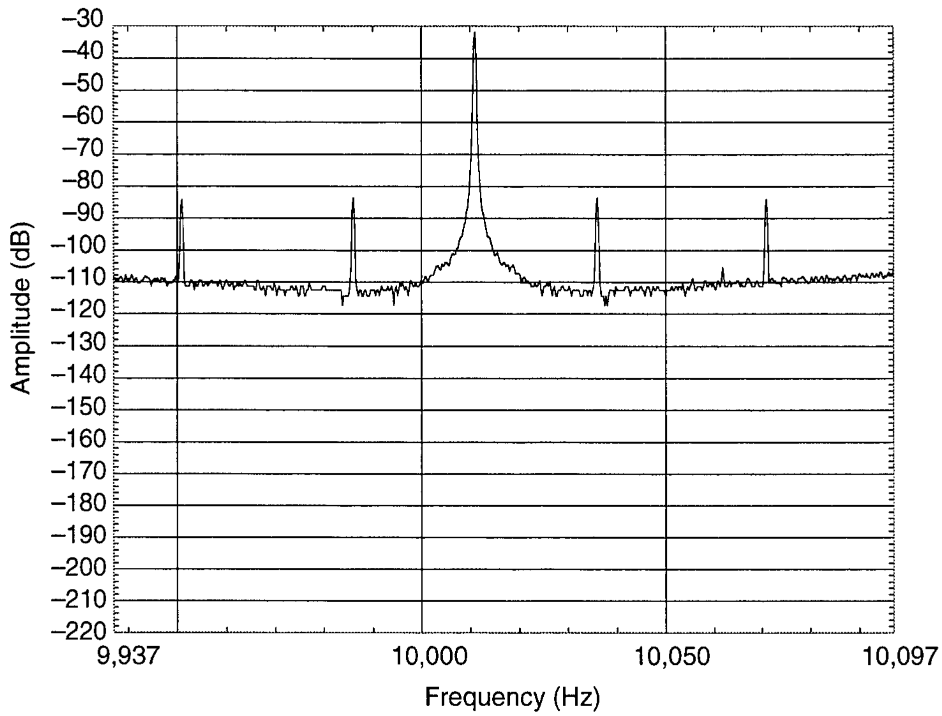


Figure C-29. Oscillator 96, 5 g at 25 Hz, screw sideways, vertical vibration, $\gamma = 5.63 \times 10^{-9}/g$.

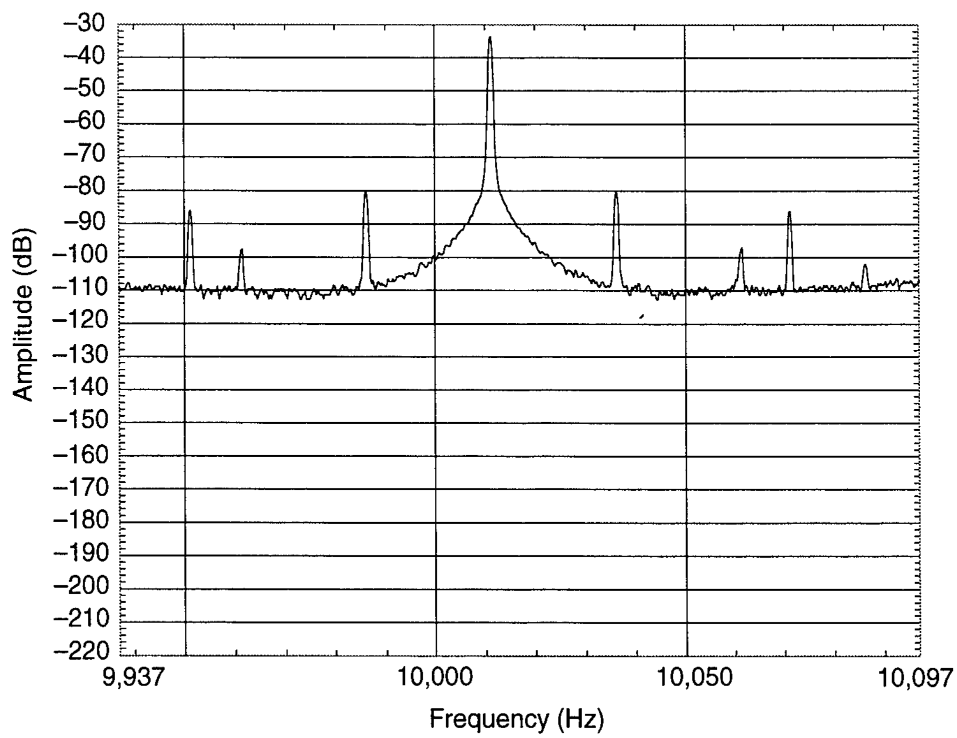


Figure C-30. Oscillator 96, 8 g at 25 Hz, screw sideways, vertical vibration, $\gamma = 5.58 \times 10^{-9}/g$.

Figure C-31. Oscillator 96, 1 g at 50 Hz, screw sideways, vertical vibration, $\gamma = 6.32 \times 10^{-9}/g$.

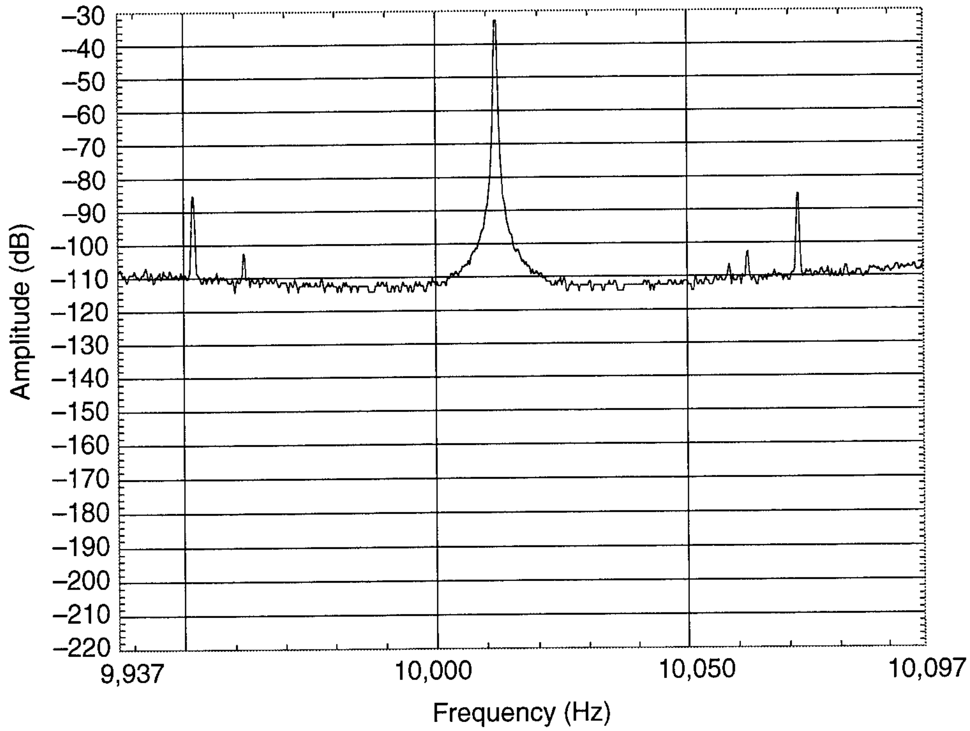


Figure C-32. Oscillator 96, 5 g at 50 Hz, screw sideways, vertical vibration, $\gamma = 5.03 \times 10^{-9}/g$.

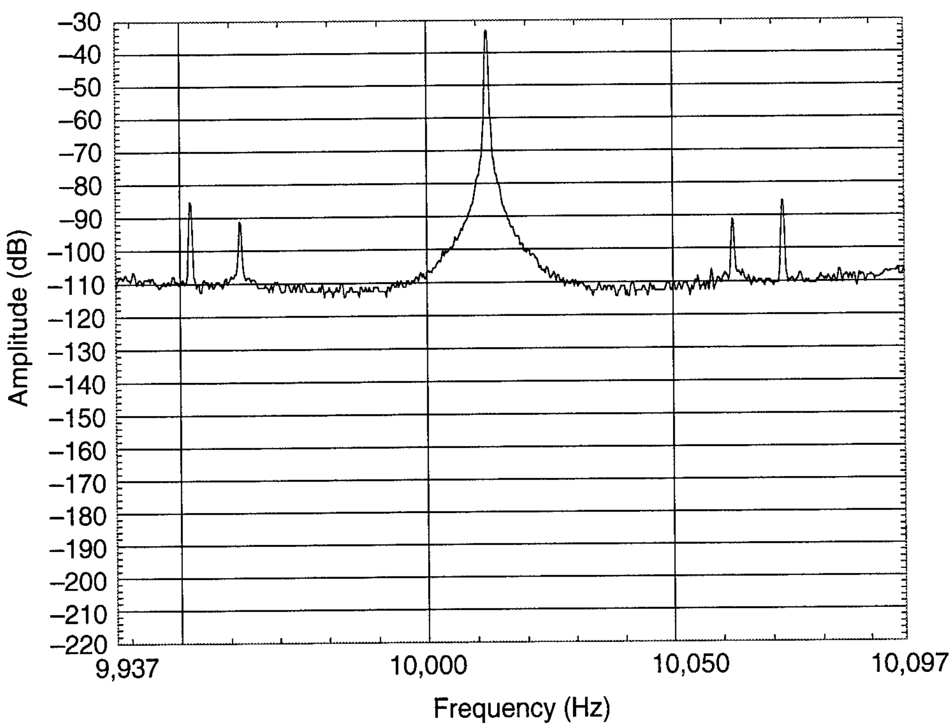


Figure C-33. Oscillator 96, 10 g at 50 Hz, screw sideways, vertical vibration, $\gamma = 3.98 \times 10^{-9}/g$.

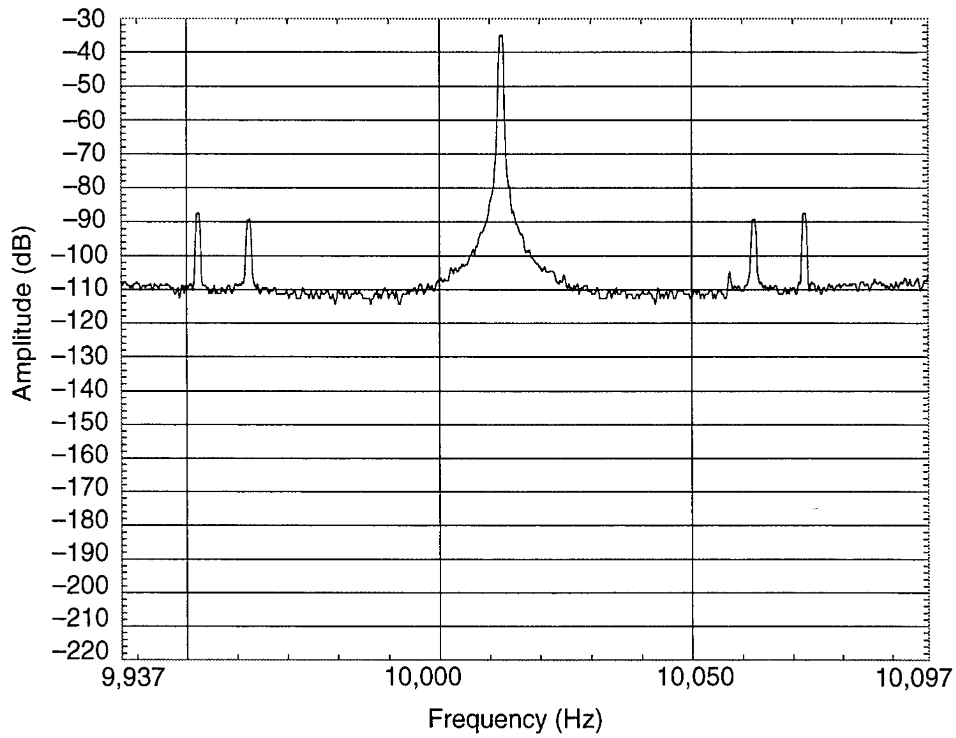


Figure C-34. Oscillator 96, 25 g at 50 Hz, screw sideways, vertical vibration, $\gamma = 7.13 \times 10^{-9}/g$.

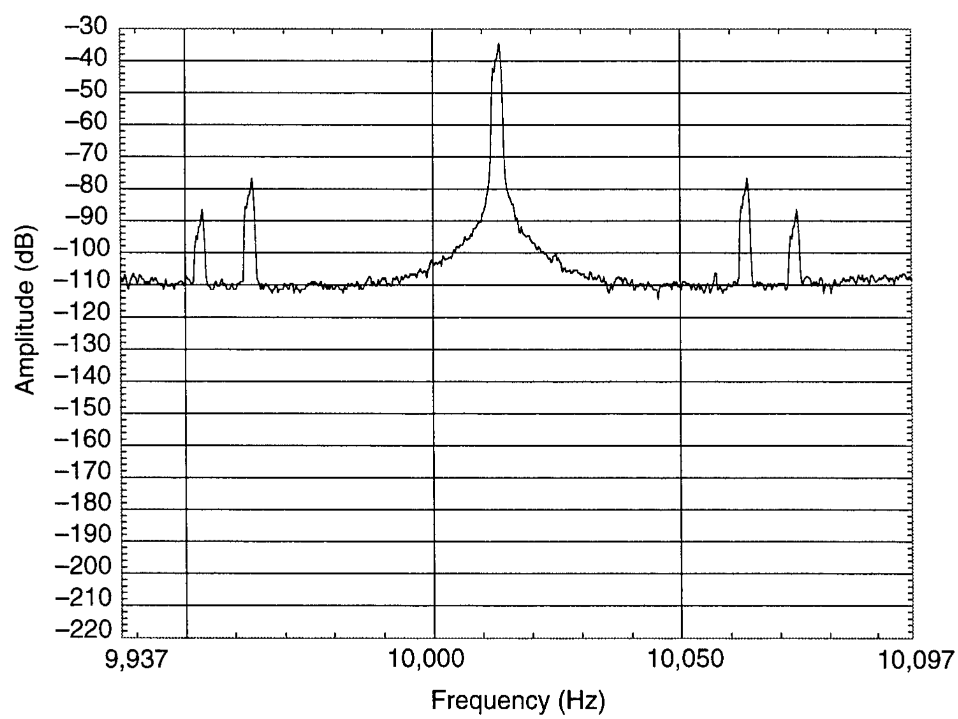


Figure C-35. Oscillator 96, 31 g at 50 Hz, screw sideways, vertical vibration, $\gamma = 5.75 \times 10^{-9}/g$.

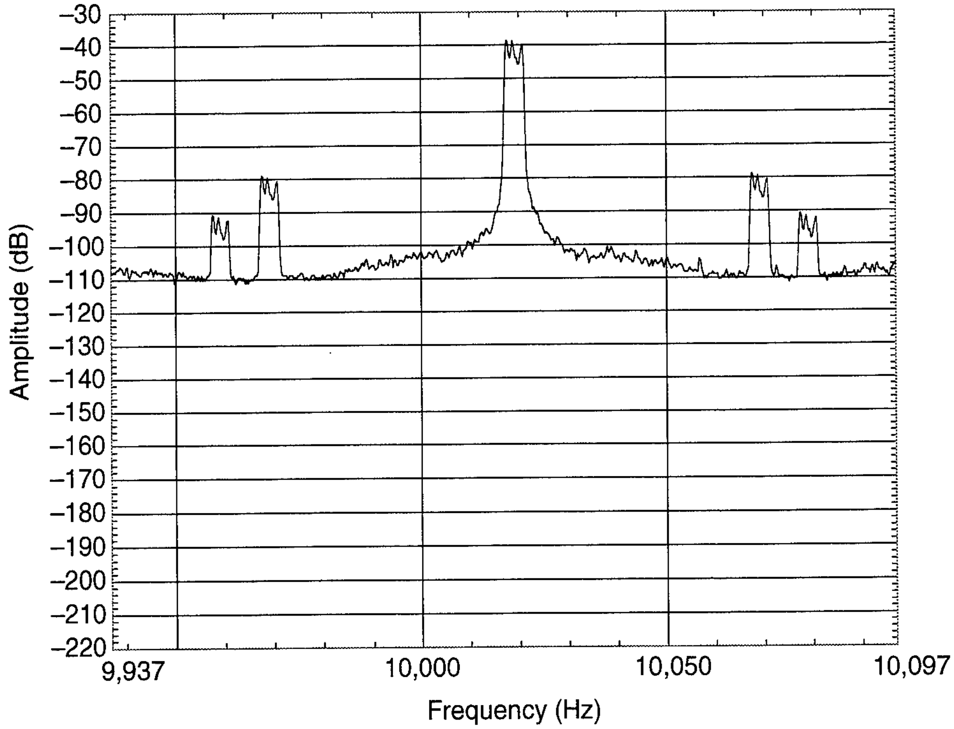


Figure C-36. Oscillator 96, 1 g at 500 Hz, screw sideways, vertical vibration, $\gamma = 2.24 \times 10^{-8}/g$.

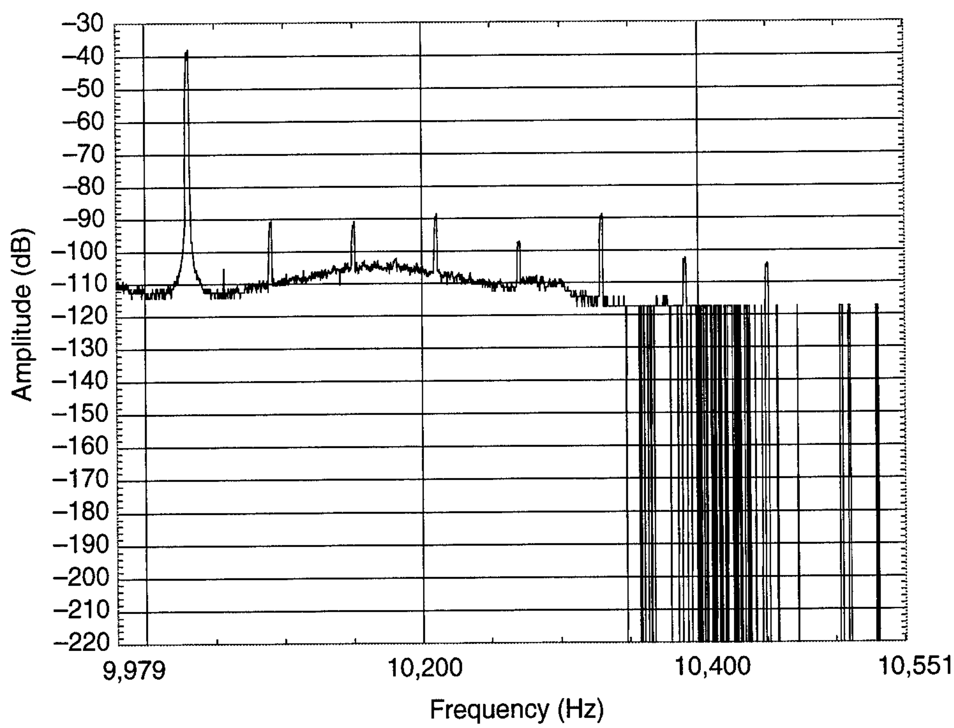


Figure C-37. Oscillator 96, 5 g at 500 Hz, screw sideways, vertical vibration, $\gamma = 1.13 \times 10^{-8}/g$.

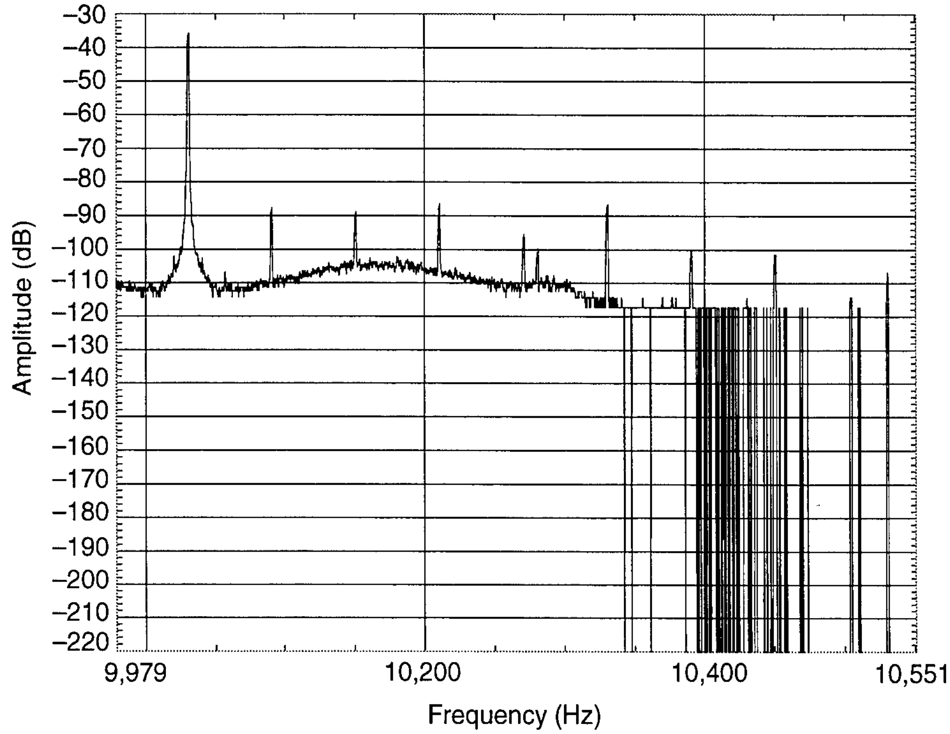


Figure C-38. Oscillator 96, 10 g at 500 Hz, screw sideways, vertical vibration, $\gamma = 7.96 \times 10^{-9}/g$.

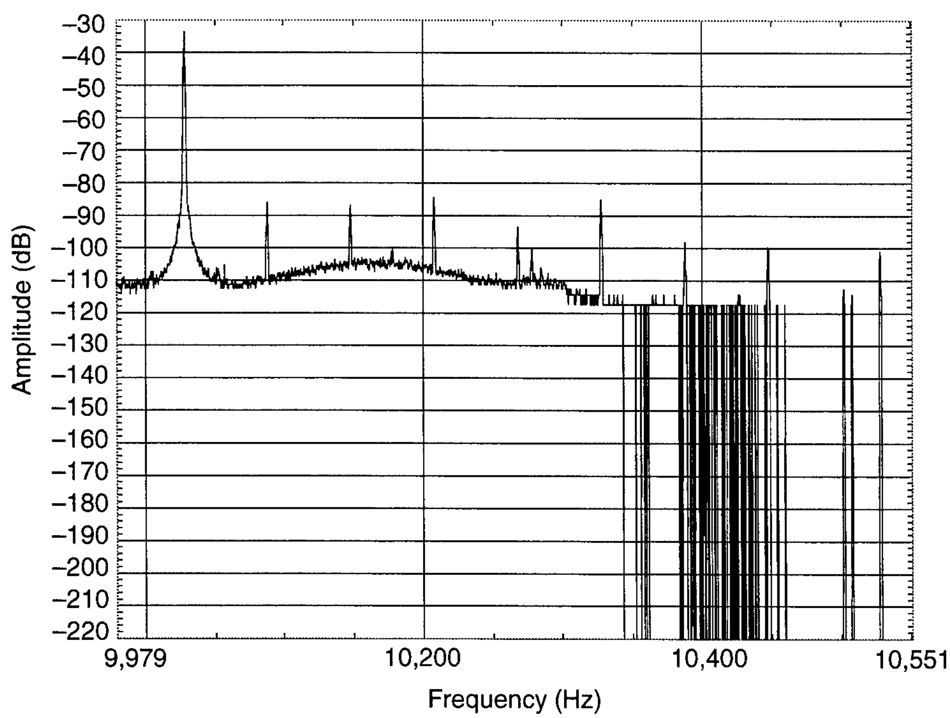


Figure C-39. Oscillator 96, 25 g at 500 Hz, screw sideways, vertical vibration, $\gamma = 6.35 \times 10^{-9}/g$.

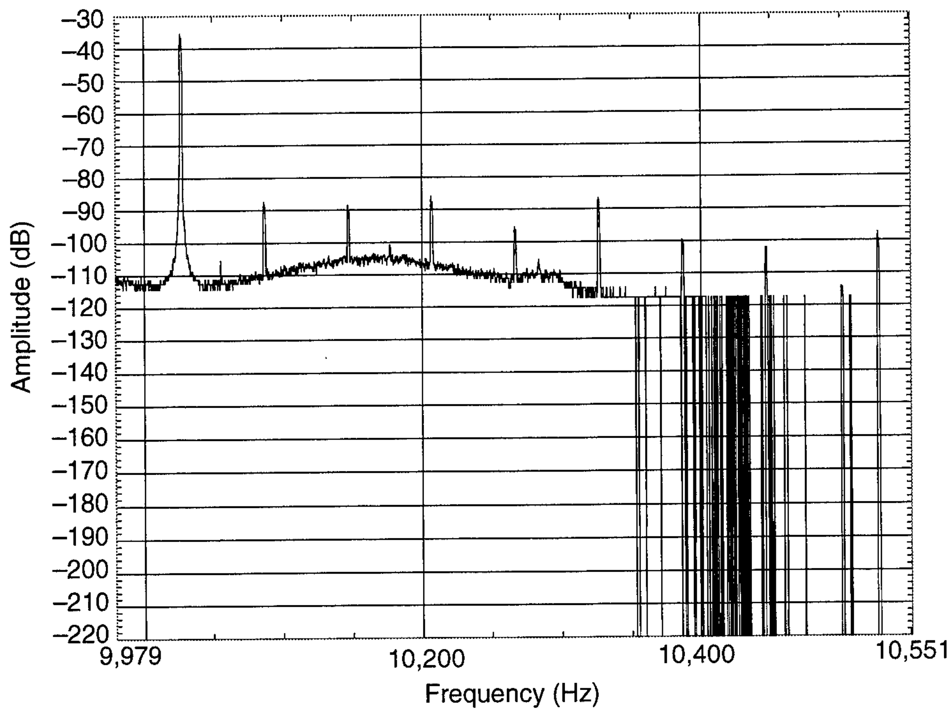


Figure C-40. Oscillator 96, 40 g at 500 Hz, screw sideways, vertical vibration, $\gamma = 4.99 \times 10^{-9}/g$.

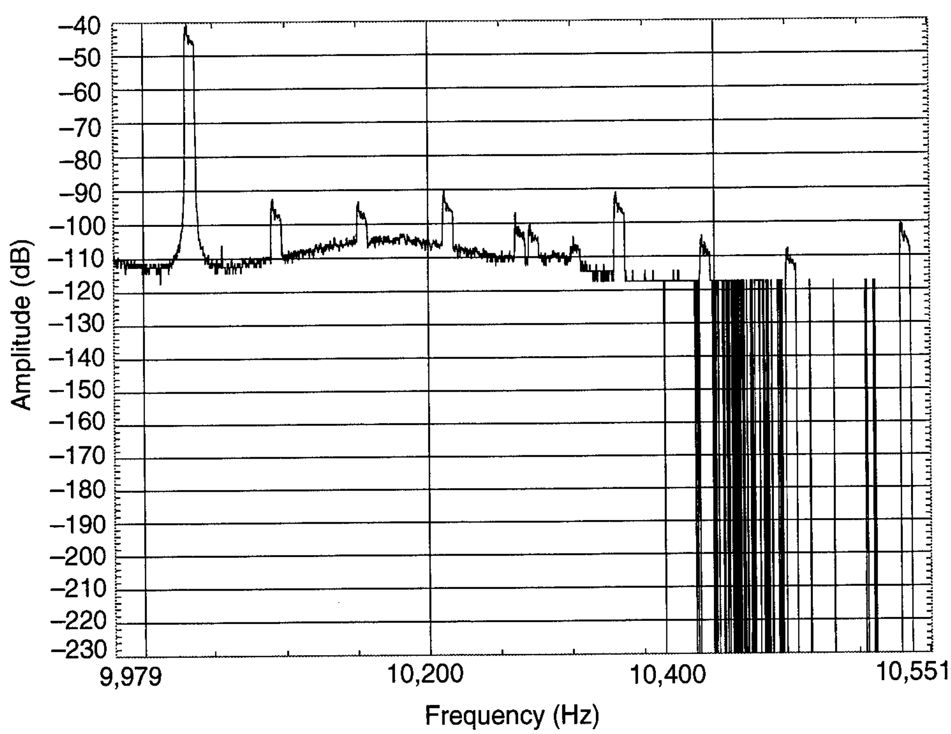


Figure C-41. Baseline 2 measurement oscillator 96 screw sideways, vertical vibration.

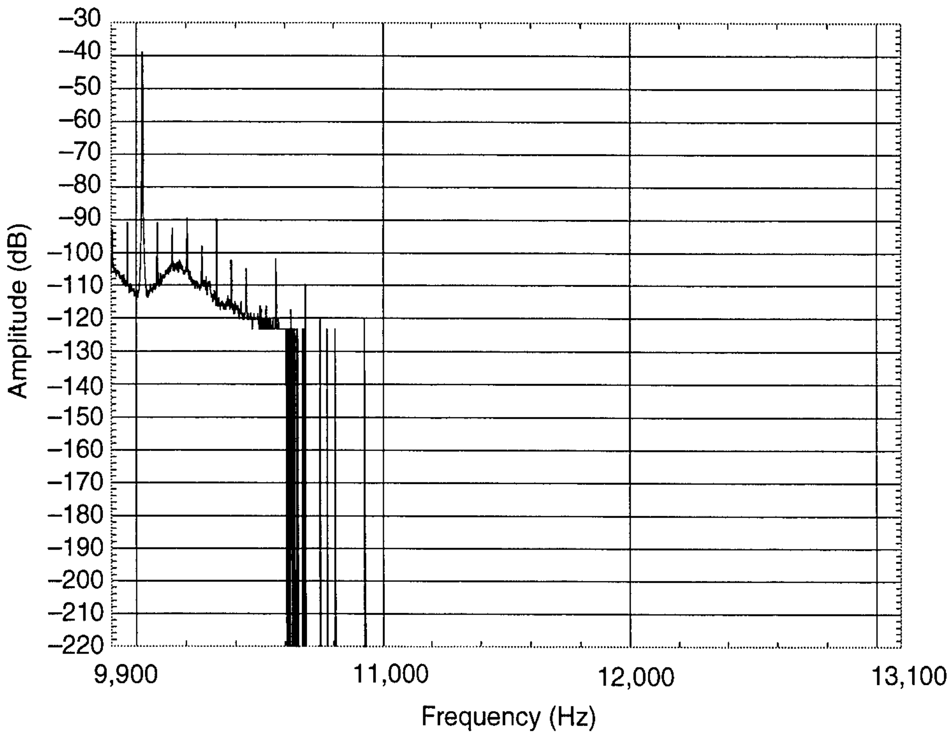


Figure C-42. Oscillator 96, 1 g at 1000 Hz, screw sideways, vertical vibration, can't resolve.

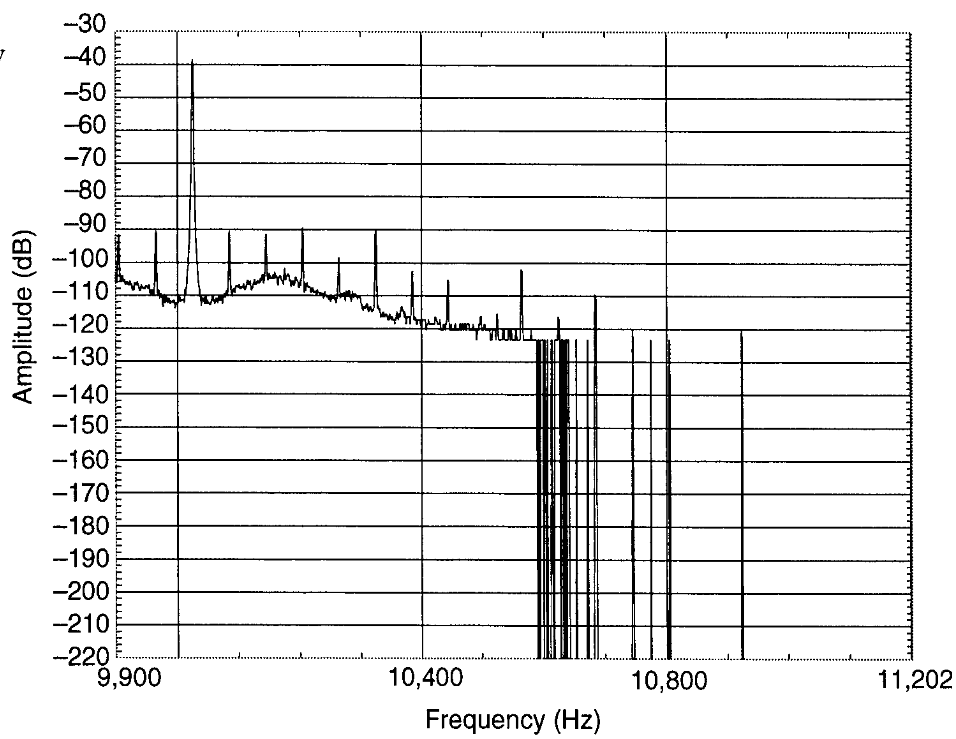


Figure C-43. Oscillator 96, 5 g at 1000 Hz, screw sideways, vertical vibration, $\gamma = 7.99 \times 10^{-9}/g$.

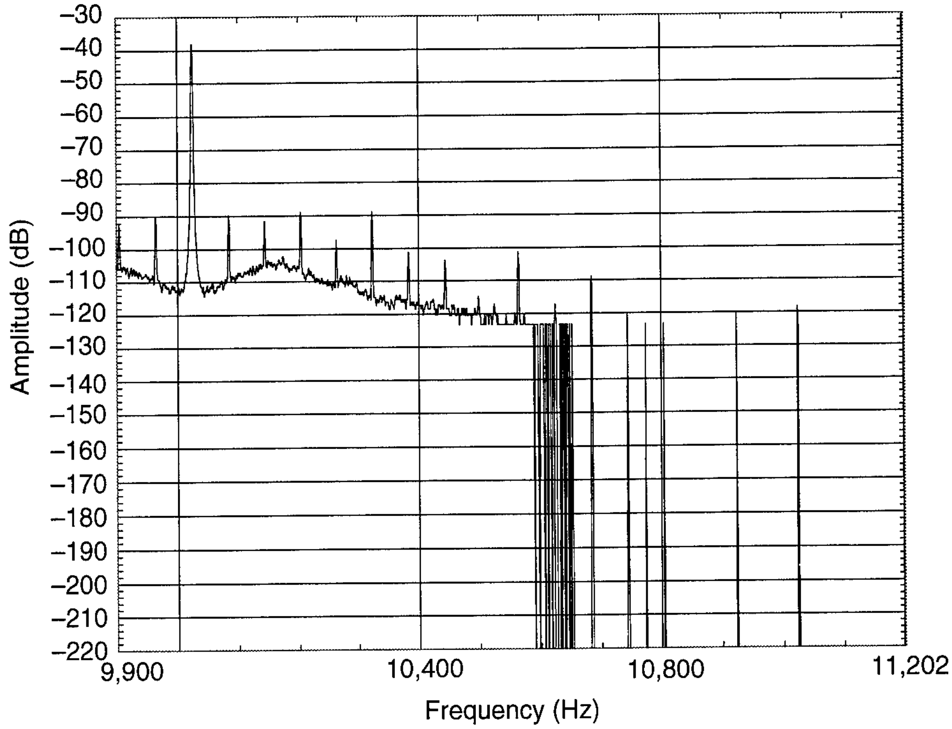


Figure C-44. Oscillator 96, 10 g at 1000 Hz, screw sideways, vertical vibration, $\gamma = 7.98 \times 10^{-9}/g$.

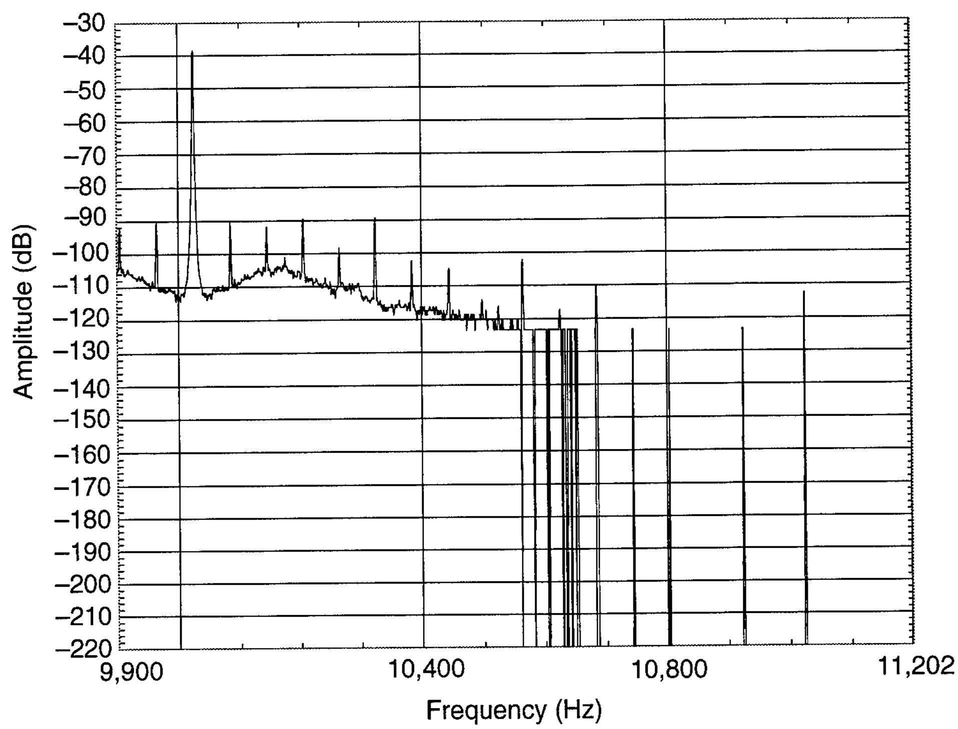


Figure C-45. Oscillator 96, 25 g at 1000 Hz, screw sideways, vertical vibration, $\gamma = 8.99 \times 10^{-9}/g$.

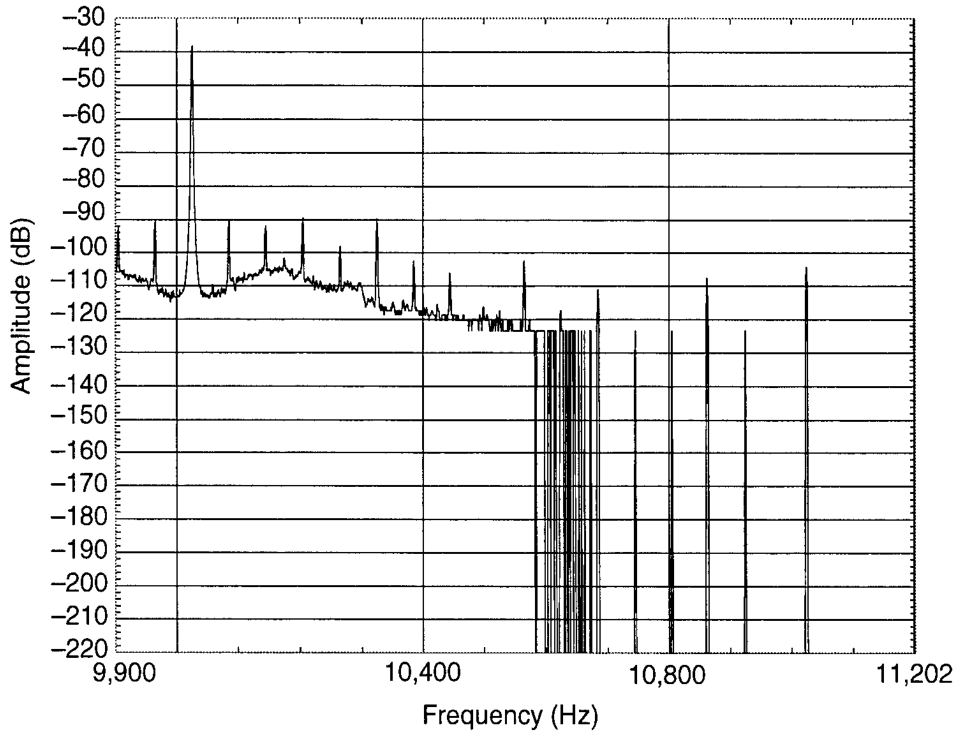
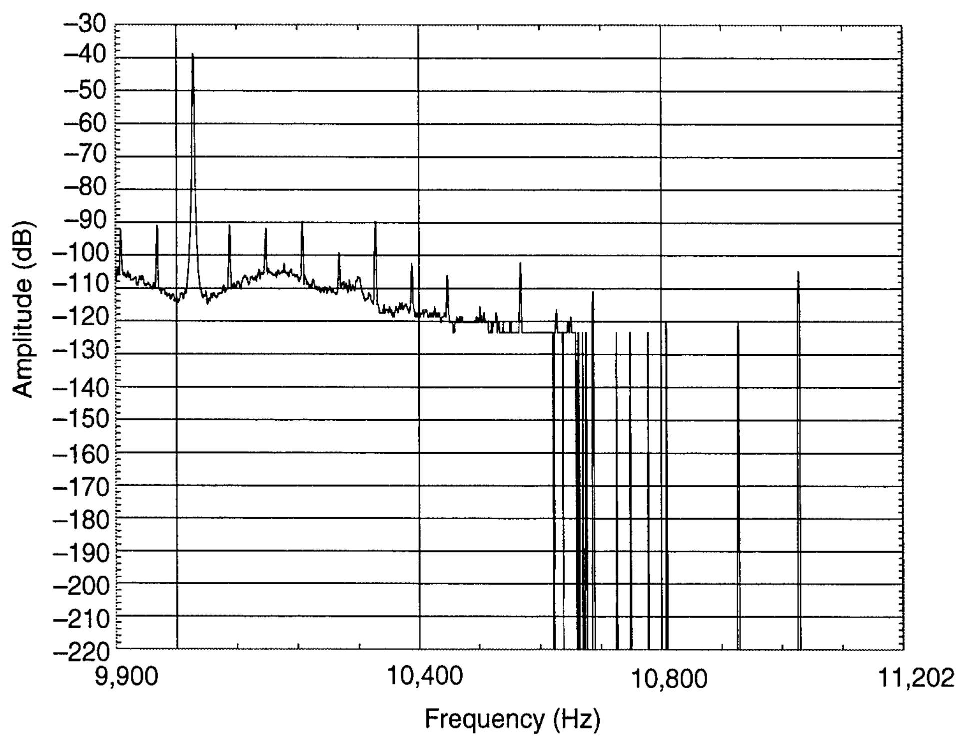


Figure C-46. Oscillator 96, 40 g at 1000 Hz, screw sideways, vertical vibration, $\gamma = 5.01 \times 10^{-9}/g$.



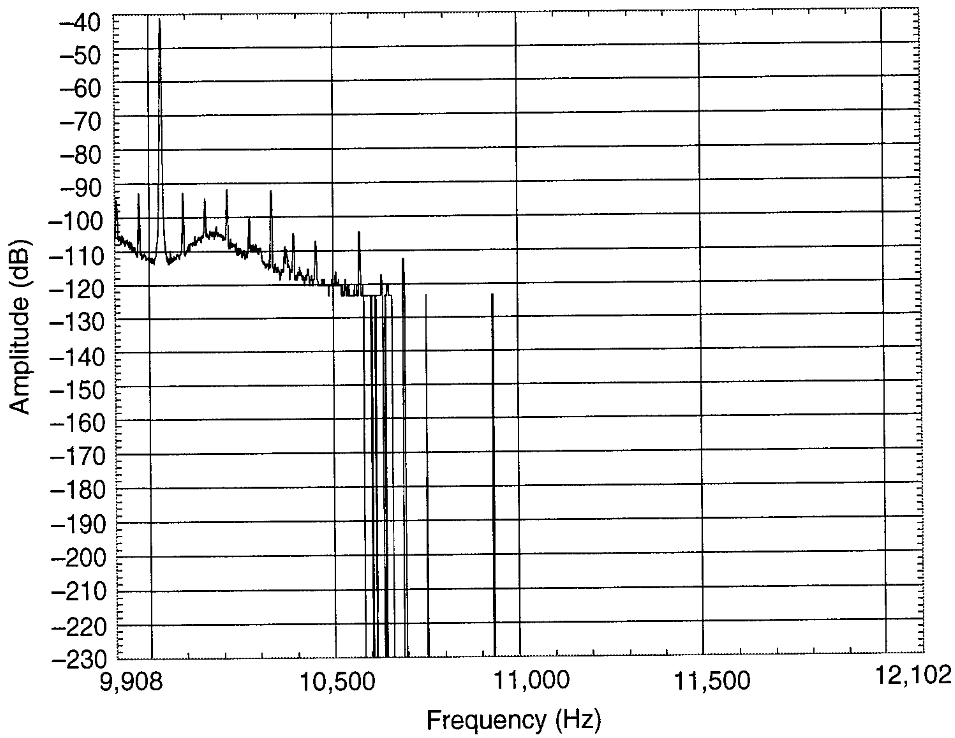


Figure C-47. Oscillator 96, 1 g at 2000 Hz, screw sideways, vertical vibration, Can't Resolve.

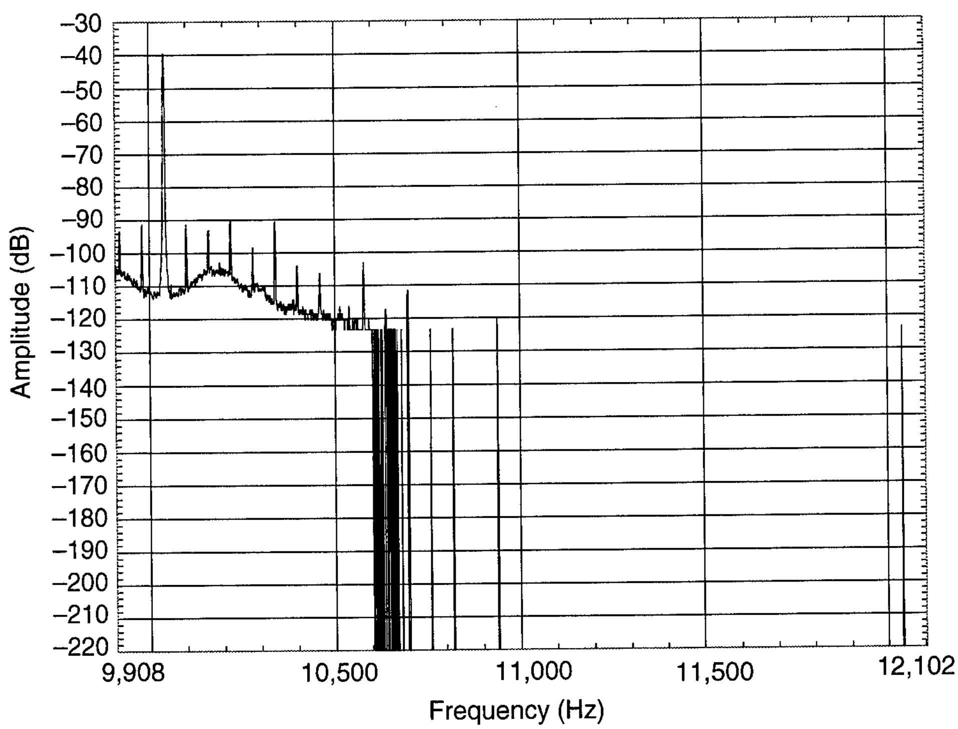


Figure C-48. Oscillator 96, 5 g at 2000 Hz, screw sideways, vertical vibration, $\gamma = 1.01 \times 10^{-8}/g$.

Figure C-49. Oscillator 96, 10 g at 2000 Hz, screw sideways, vertical vibration, $\gamma = 1.01 \times 10^{-8}/g$.

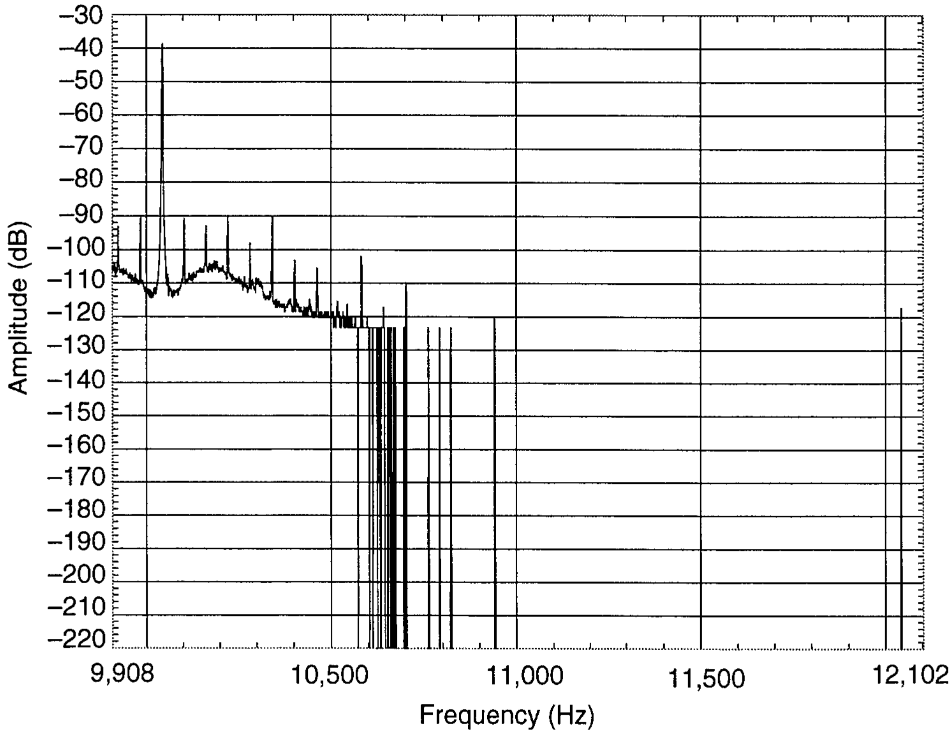
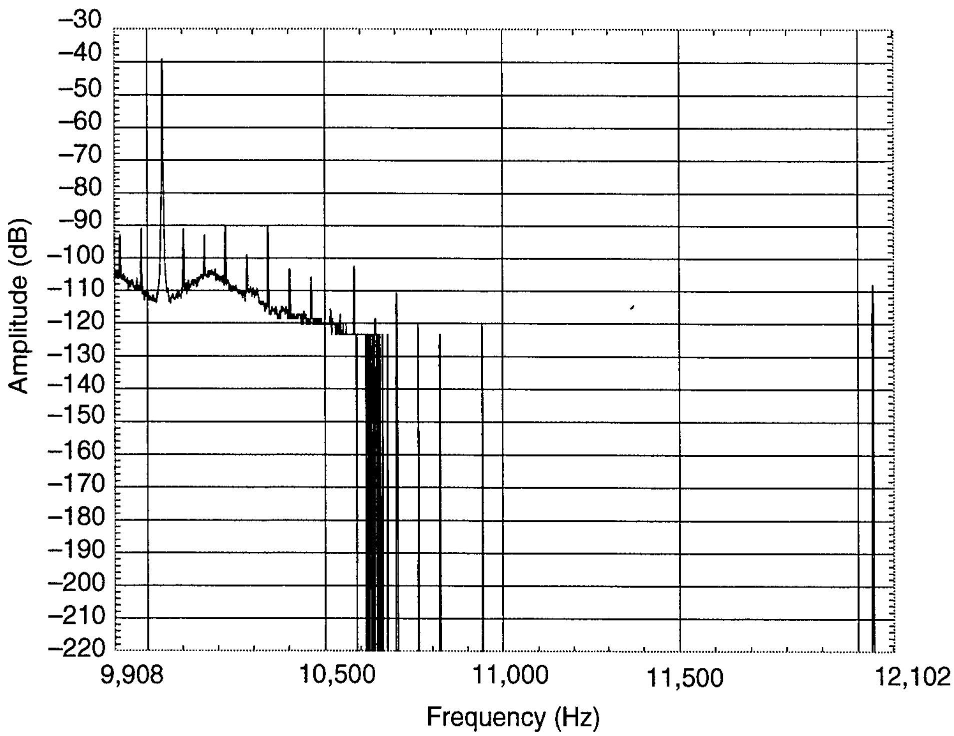


Figure C-50. Oscillator 96, 25 g at 2000 Hz, screw sideways, vertical vibration, $\gamma = 1.13 \times 10^{-8}/g$.



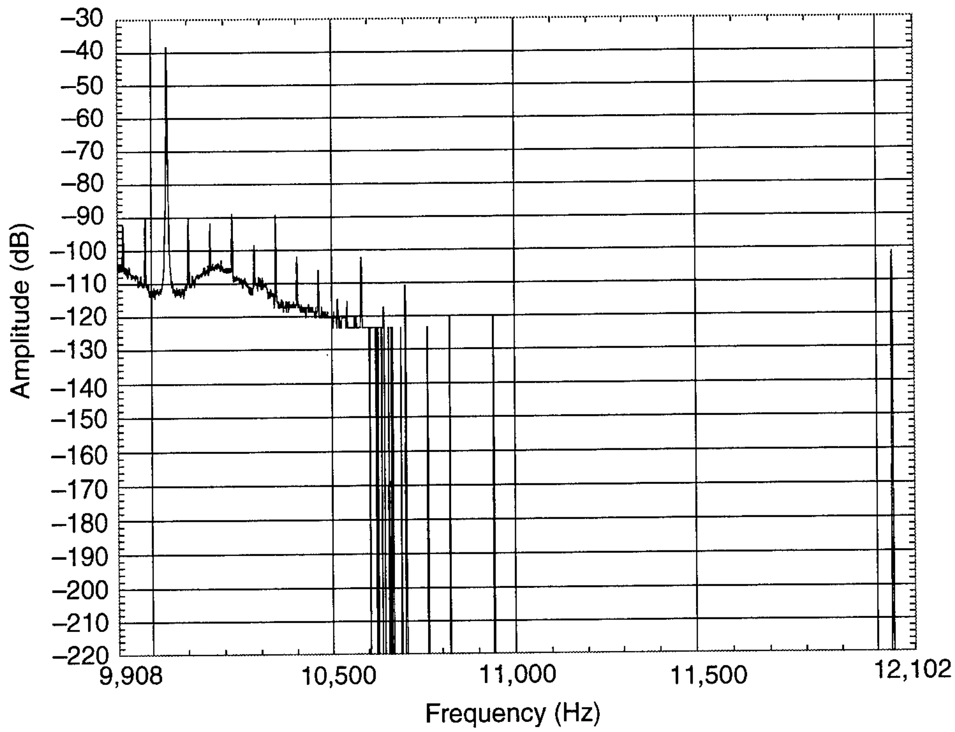


Figure C-51. Oscillator 96, 39.4 g at 2000 Hz, screw sideways, vertical vibration, $\gamma = 1.44 \times 10^{-8}/g$.

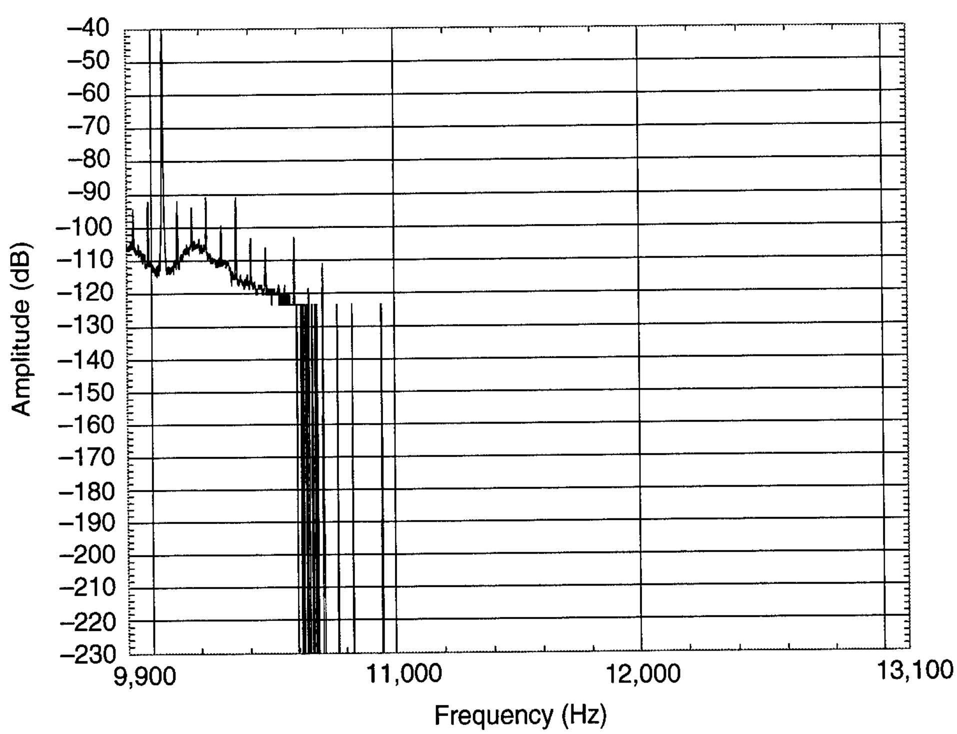


Figure C-52. Oscillator 96, 5 g at 3000 Hz, screw sideways, vertical vibration, can't resolve.

Figure C-53. Oscillator 96, 10 g at 3000 Hz, screw sideways, vertical vibration, can't resolve.

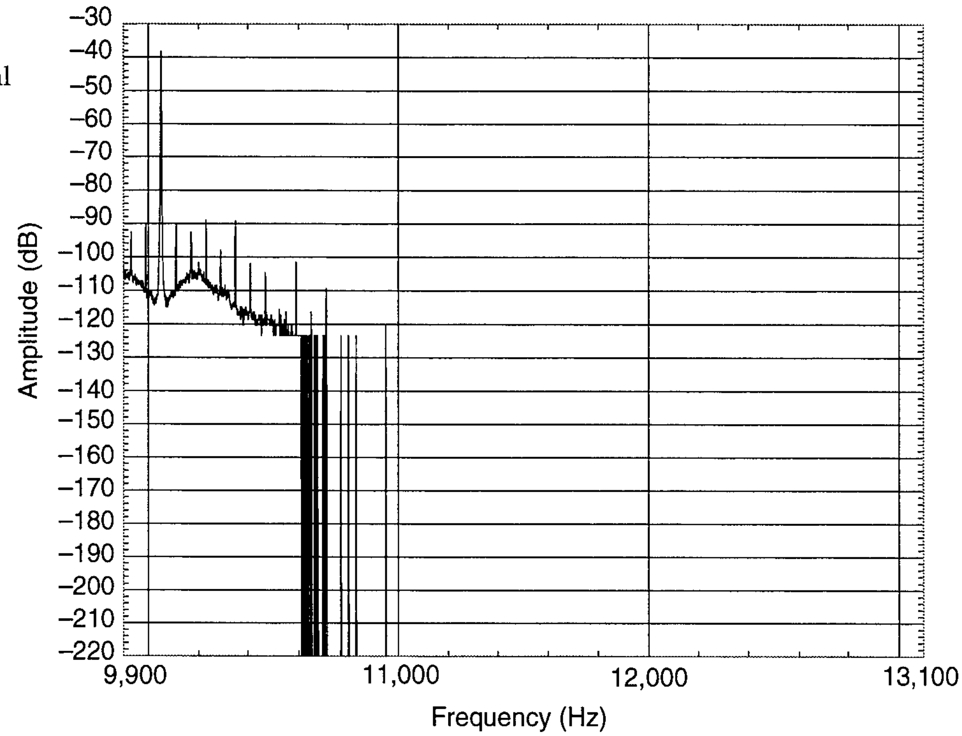


Figure C-54. Oscillator 96, 25 g at 3000 Hz, screw sideways, vertical vibration, $\gamma = 2.70 \times 10^{-9}/g$.

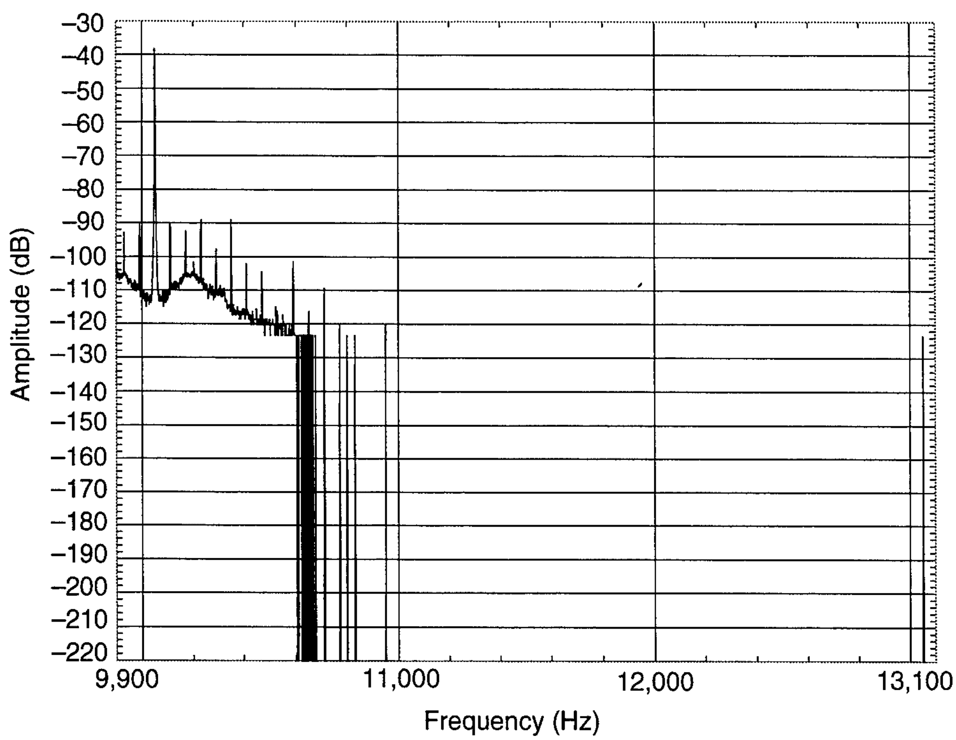


Figure C-55. Oscillator 96, 40 g at 3000 Hz, screw sideways, vertical vibration, $\gamma = 3.36 \times 10^{-9}/g$.

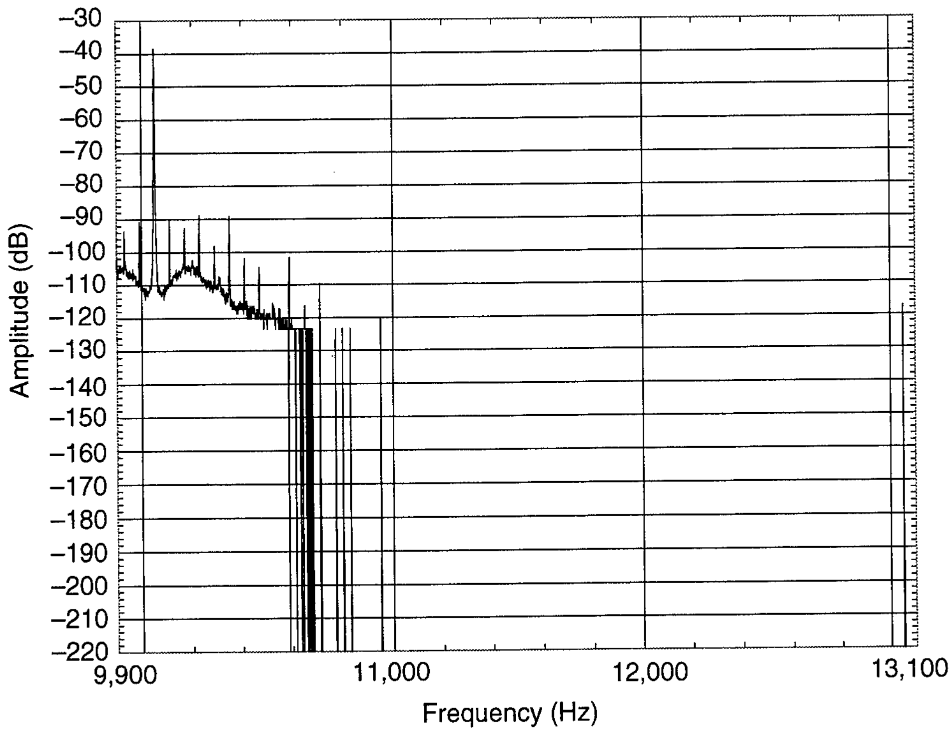


Figure C-56. Baseline measurement oscillator 96, device horizontal, vertical vibration.

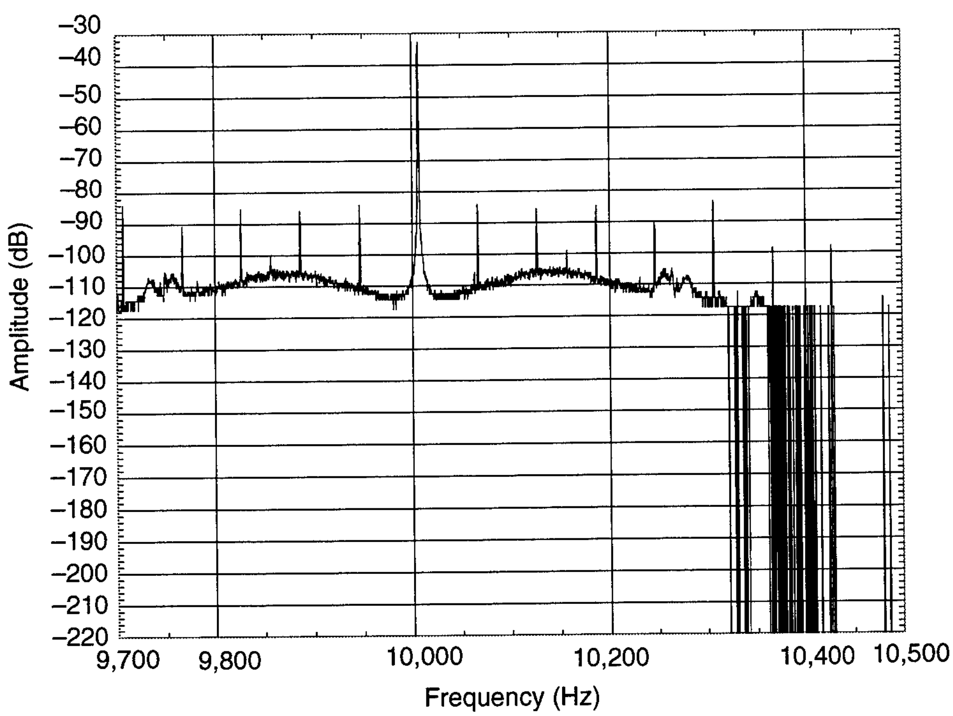


Figure C-57. Oscillator 96, 0.3 g at 5 Hz, device horizontal, vertical vibration, $\gamma = 9.93 \times 10^{-9}/g$.

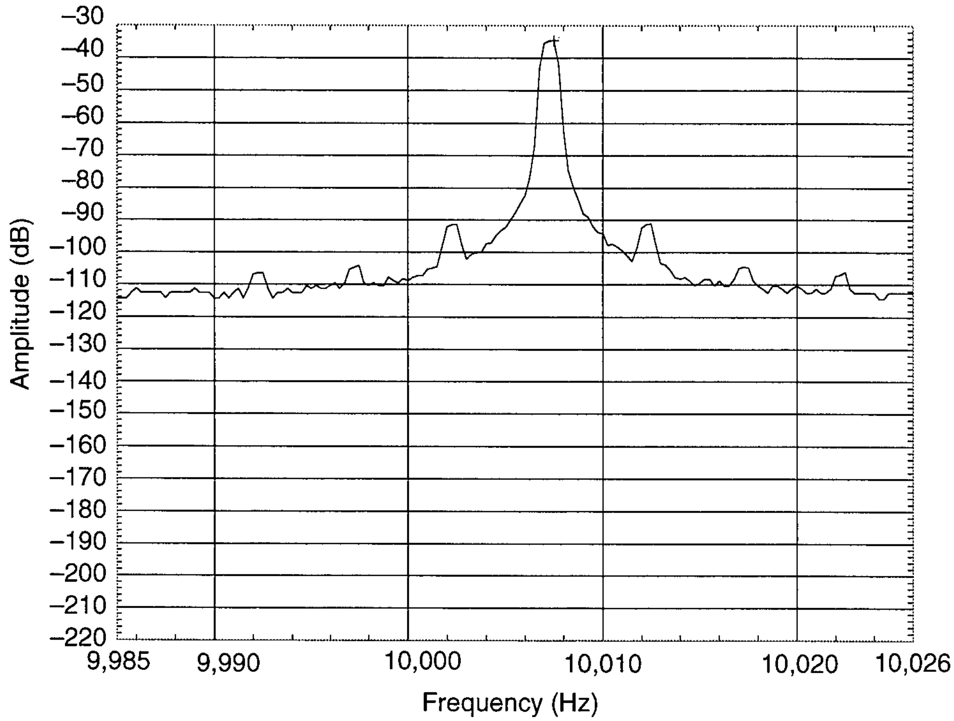


Figure C-58. Oscillator 96, 1 g at 25 Hz, device horizontal, vertical vibration, $\gamma = 1.00 \times 10^{-8}/g$.

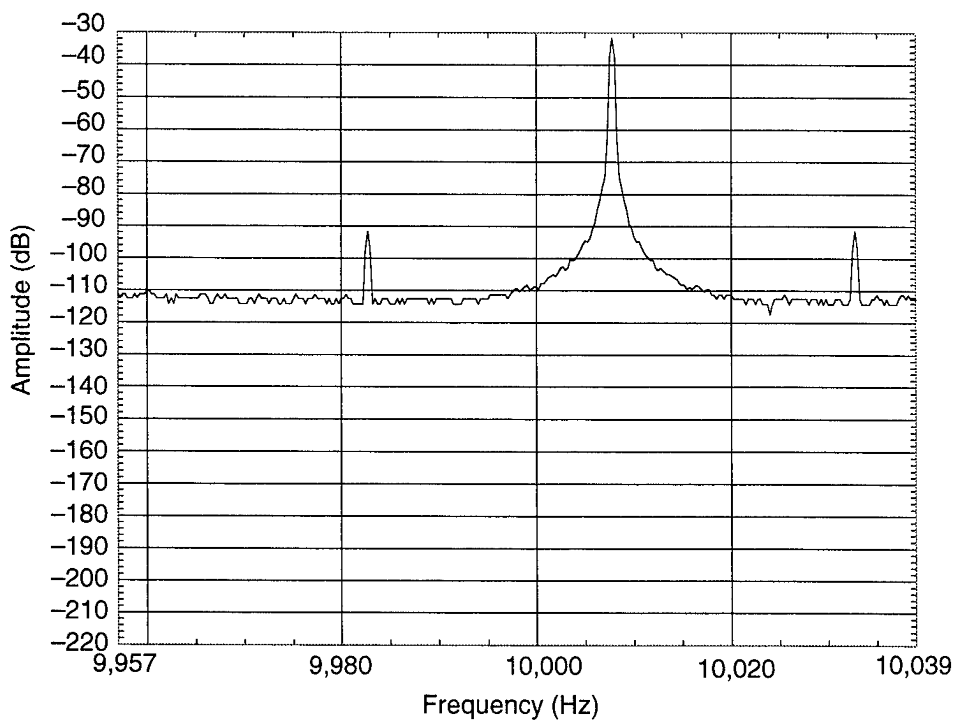


Figure C-59. Oscillator 96, 5 g at 25 Hz, device horizontal, vertical vibration, $\gamma = 1.00 \times 10^{-8}/g$.

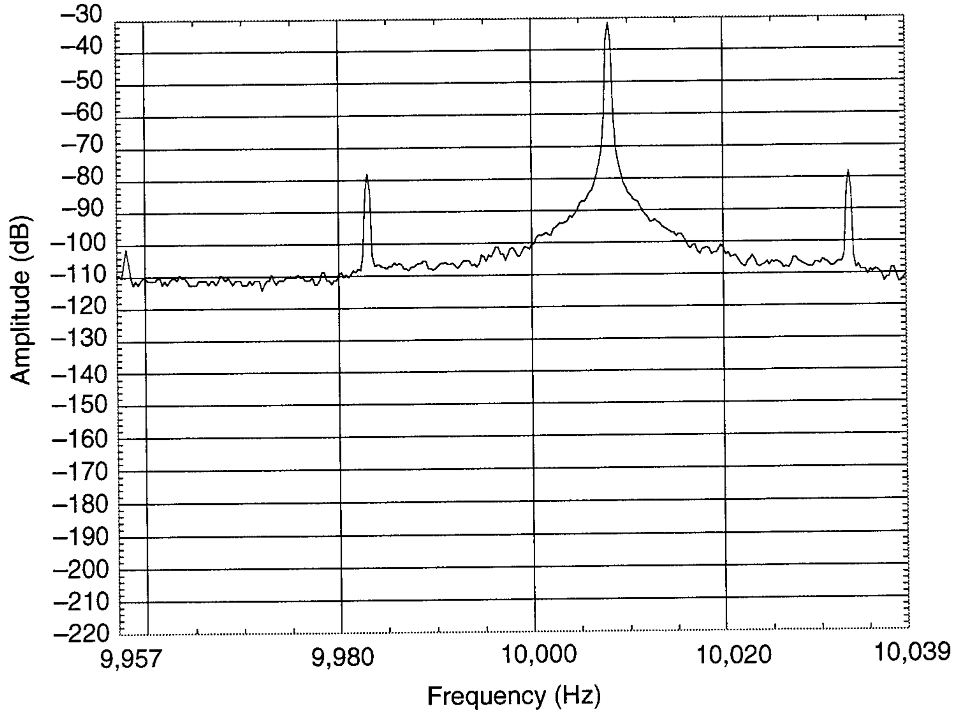


Figure C-60. Oscillator 96, 8 g at 25 Hz, device horizontal, vertical vibration, $\gamma = 8.85 \times 10^{-9}/g$.

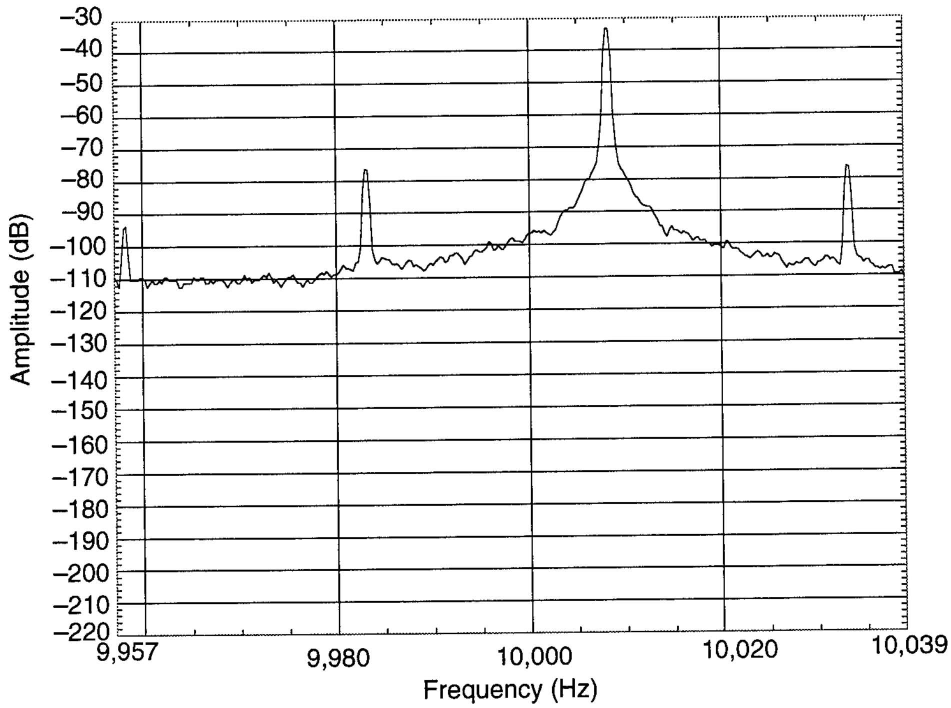


Figure C-61. Oscillator 96, 1 g at 50 Hz, device horizontal, vertical vibration, $\gamma = 8.93 \times 10^{-9}/g$.

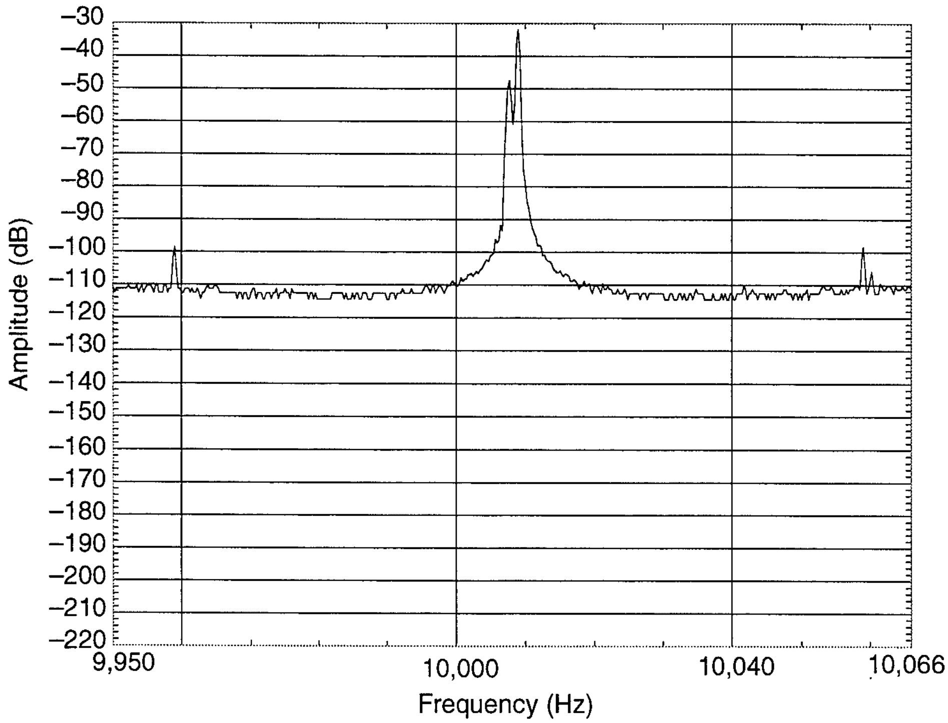


Figure C-62. Oscillator 96, 5 g at 50 Hz, device horizontal, vertical vibration, $\gamma = 1.26 \times 10^{-8}/g$.

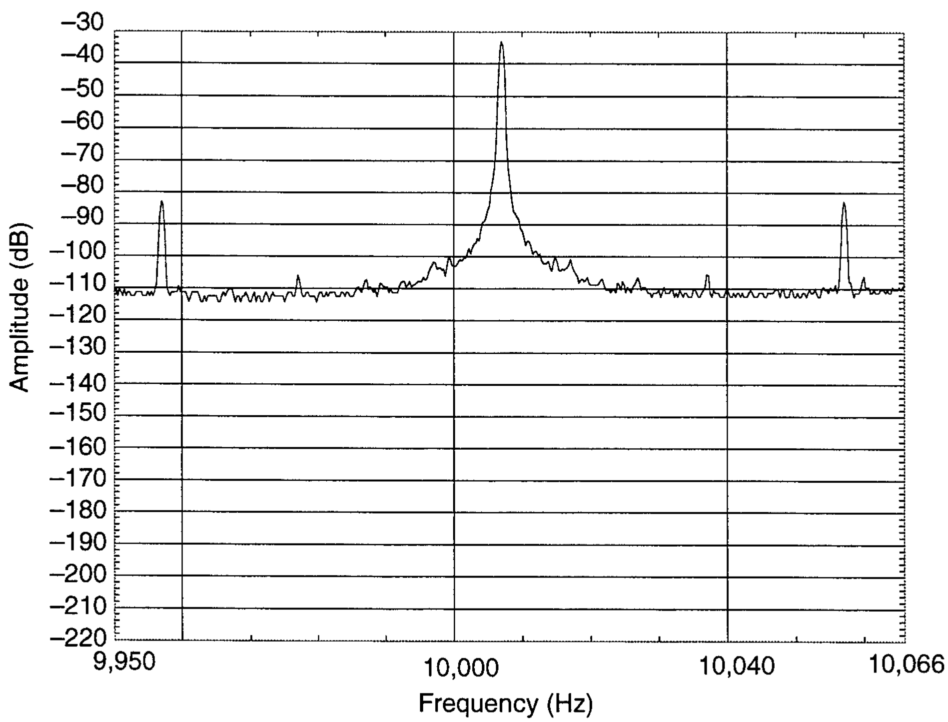


Figure C-63. Oscillator 96, 10 g at 50 Hz, device horizontal, vertical vibration, $\gamma = 8.93 \times 10^{-9}/g$.

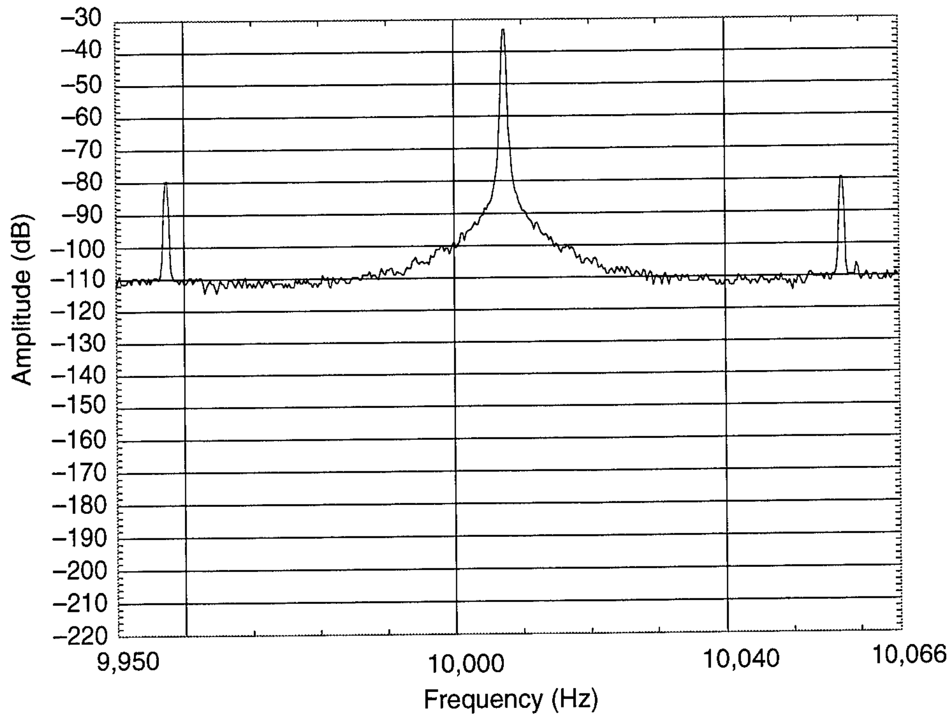


Figure C-64. Oscillator 96, 25 g at 50 Hz, device horizontal, vertical vibration, $\gamma = 1.00 \times 10^{-8}/g$.

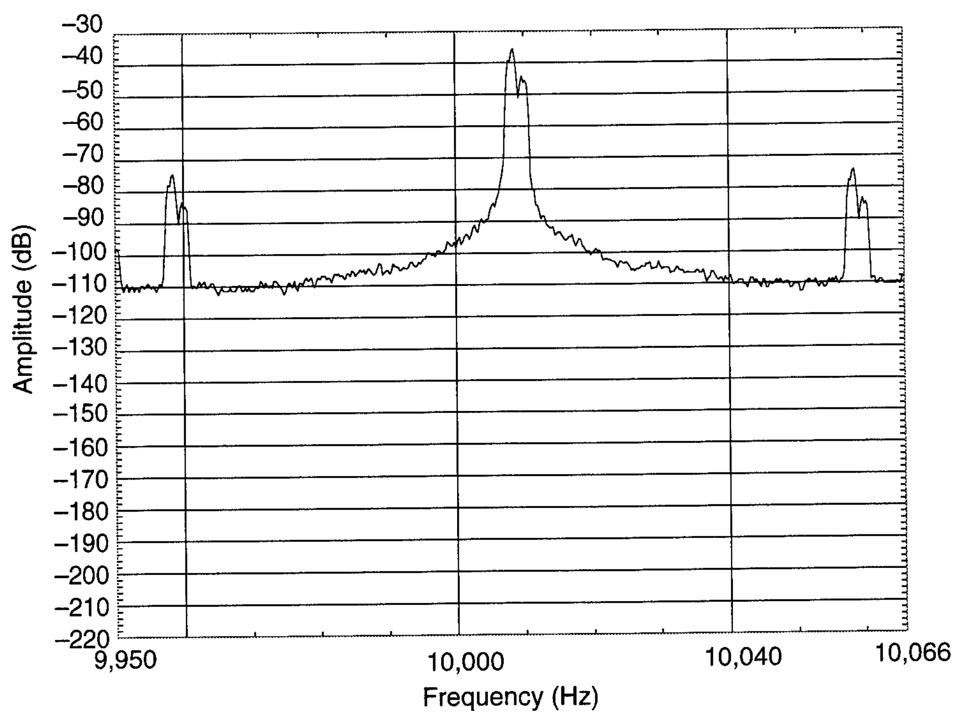


Figure C-65. Oscillator 96, Second Run, 25 g at 50 Hz, device horizontal, vertical vibration, $\gamma = 1.01 \times 10^{-8}/g$.

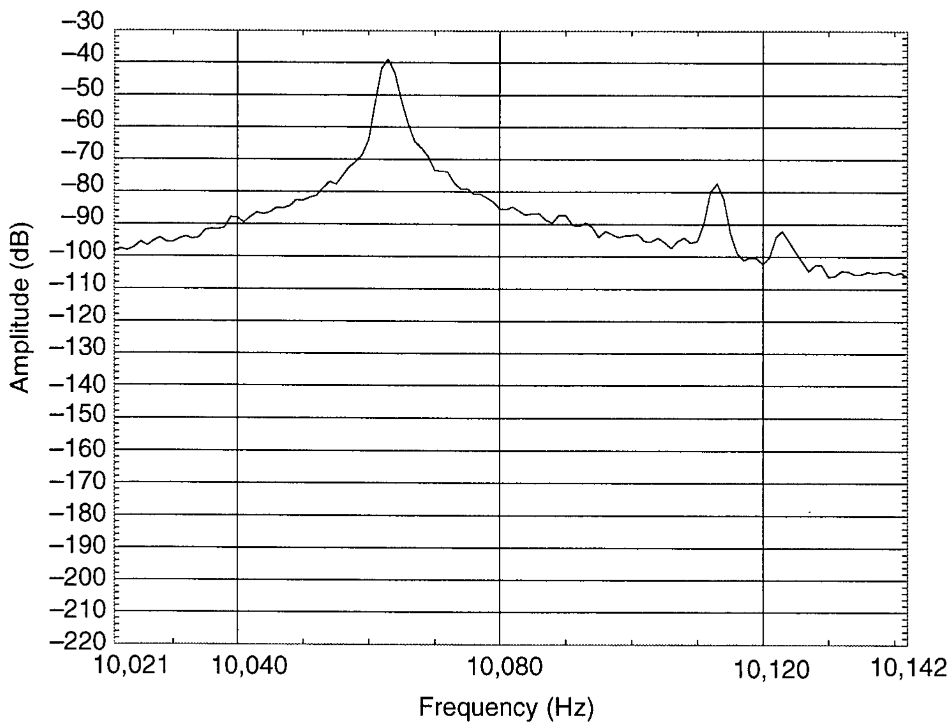


Figure C-66. Oscillator 96, 31.9 g at 50 Hz, device horizontal, vertical vibration, $\gamma = 7.89 \times 10^{-9}/g$.

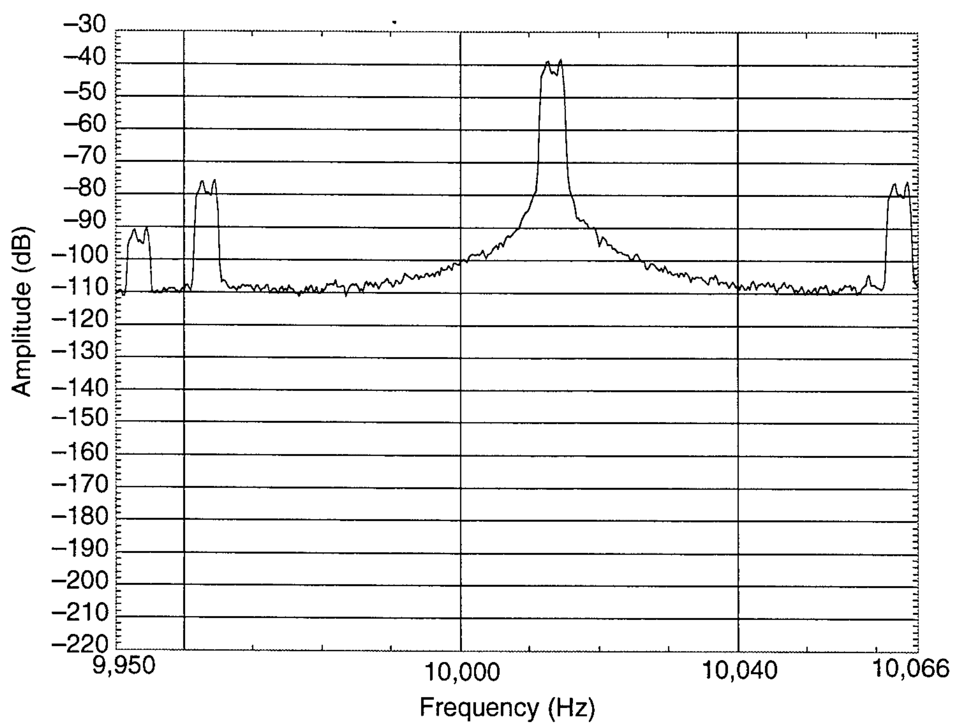


Figure C-67. Oscillator 96, 1 g at 500 Hz, device horizontal, vertical vibration, $\gamma = 2.52 \times 10^{-8}/g$.

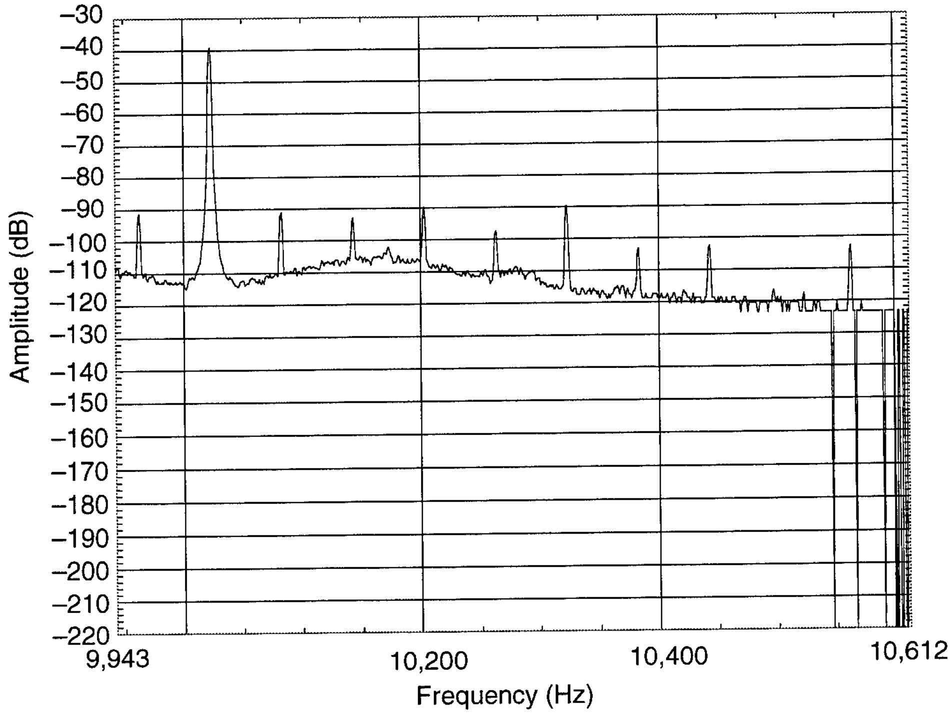


Figure C-68. Oscillator 96, 5 g at 500 Hz, device horizontal, vertical vibration, $\gamma = 7.98 \times 10^{-9}/g$.

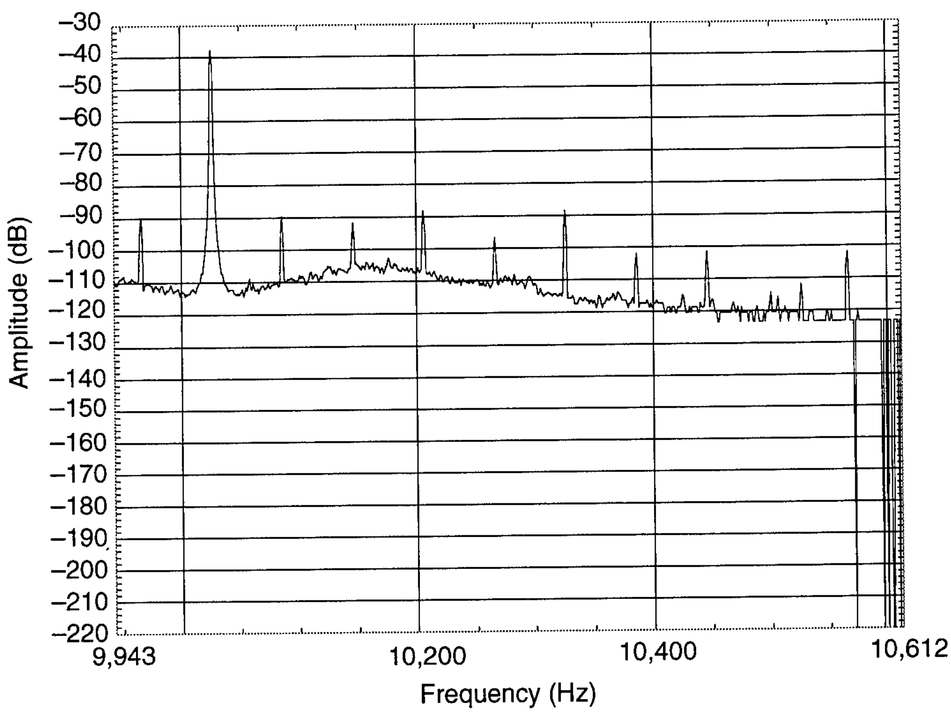


Figure C-69. Oscillator 96, 10 g at 500 Hz, device horizontal, vertical vibration, $\gamma = 5.63 \times 10^{-9}/g$.

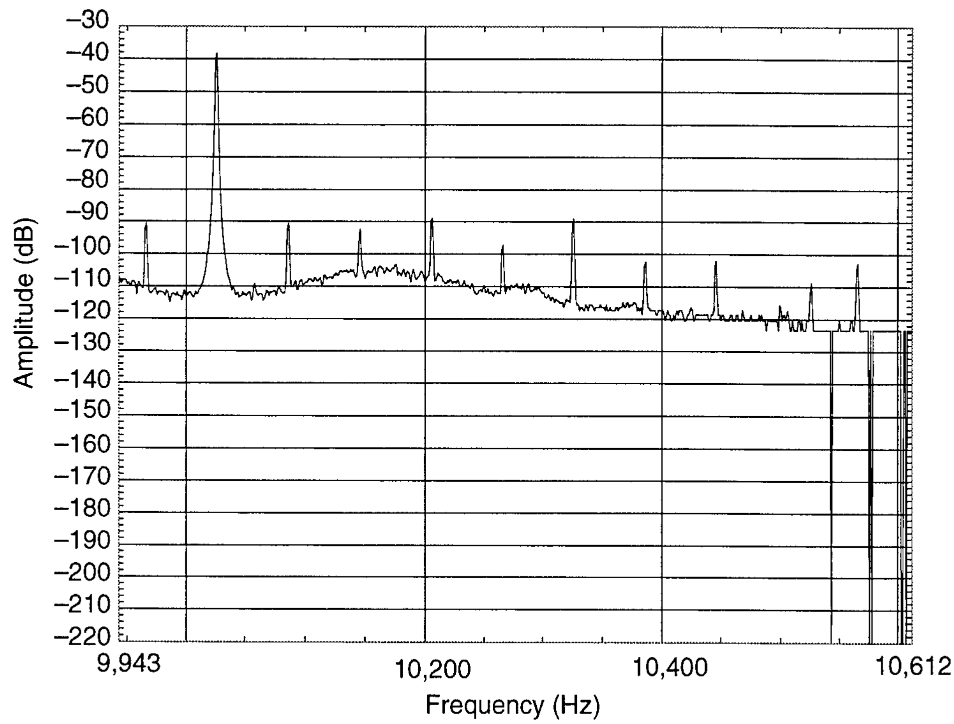
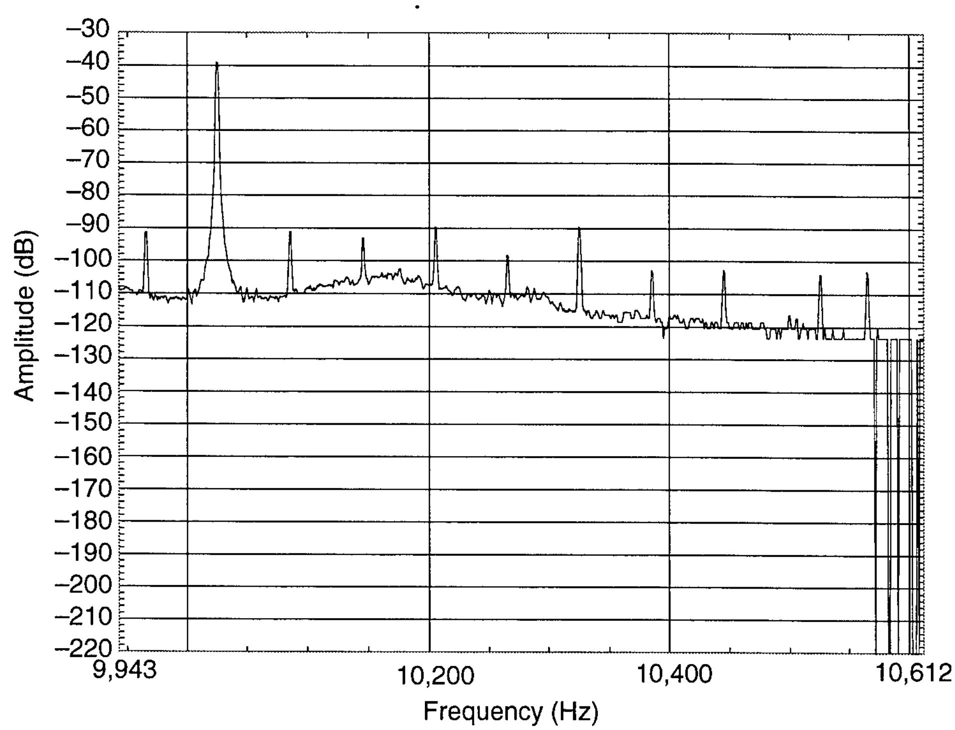


Figure C–70. Oscillator 96, 25 g at 500 Hz, device horizontal, vertical vibration, $\gamma = 4.50 \times 10^{-9}/g$.



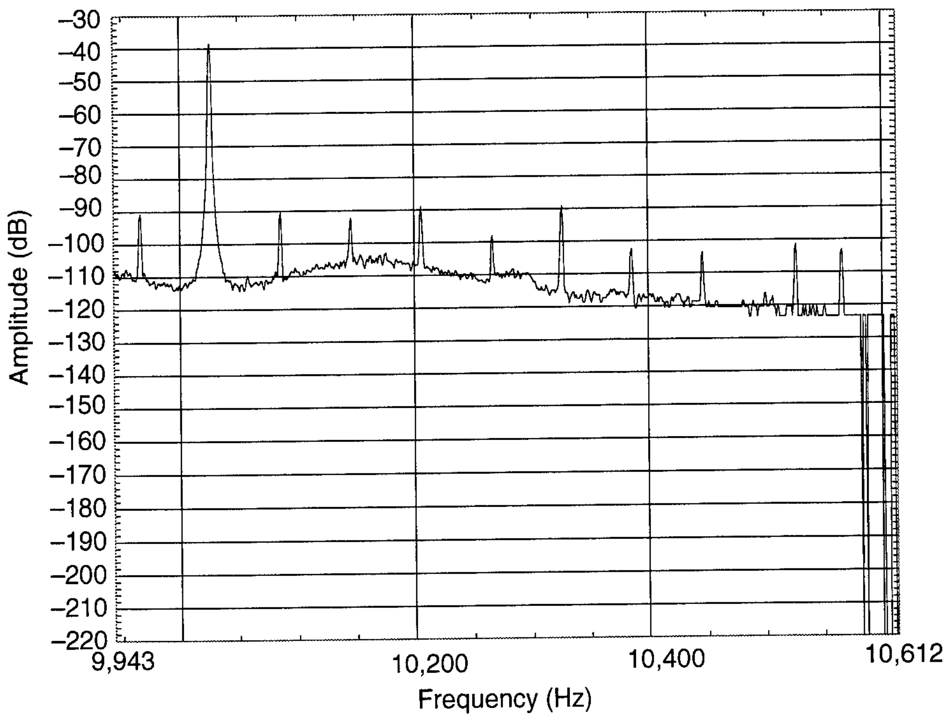


Figure C–71. Oscillator 96, 40 g at 500 Hz, device horizontal, vertical vibration, $\gamma = 3.54 \times 10^{-9}/g$.

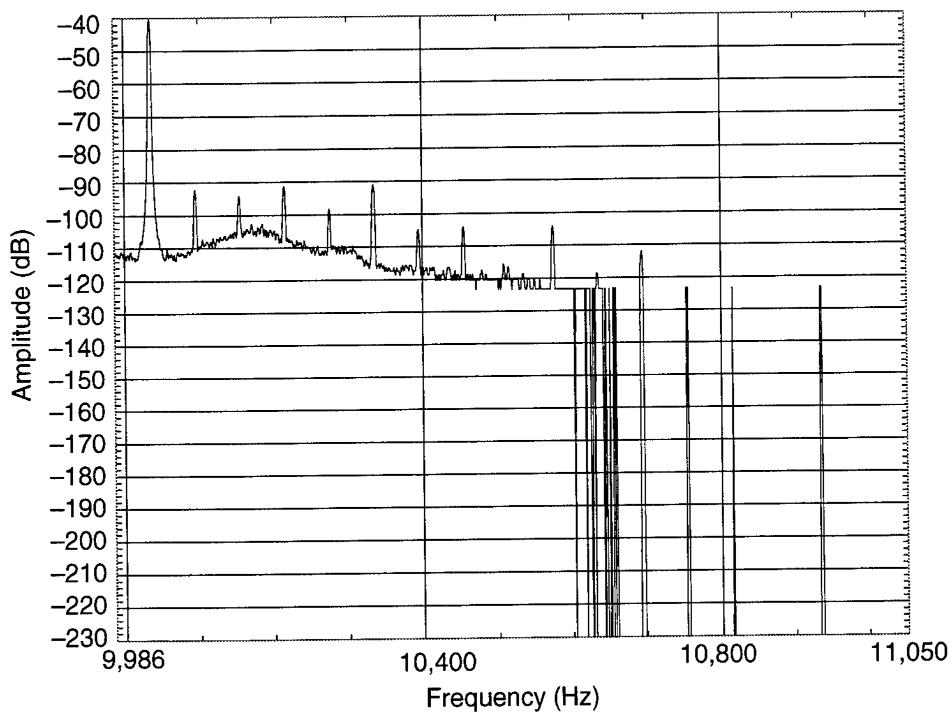


Figure C–72. Oscillator 96, 1 g at 1000 Hz, device horizontal, vertical vibration, no signal.

Figure C–73. Oscillator 96, 5 g at 1000 Hz, device horizontal, vertical vibration, no signal.

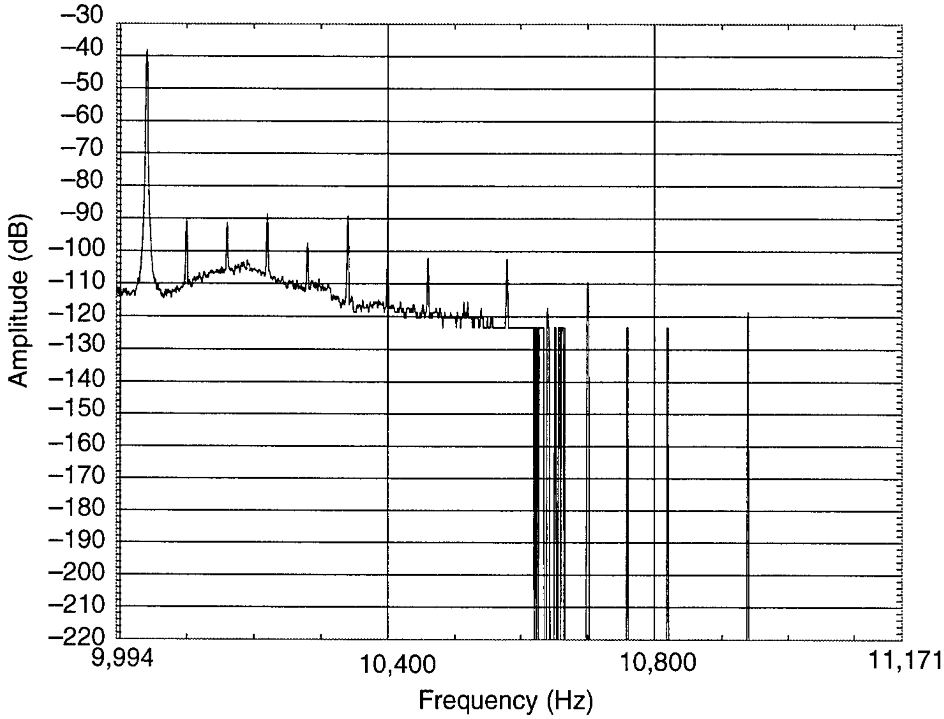


Figure C–74. Oscillator 96, 10 g at 1000 Hz, device horizontal, vertical vibration, $\gamma = 4.49 \times 10^{-9}/g$.

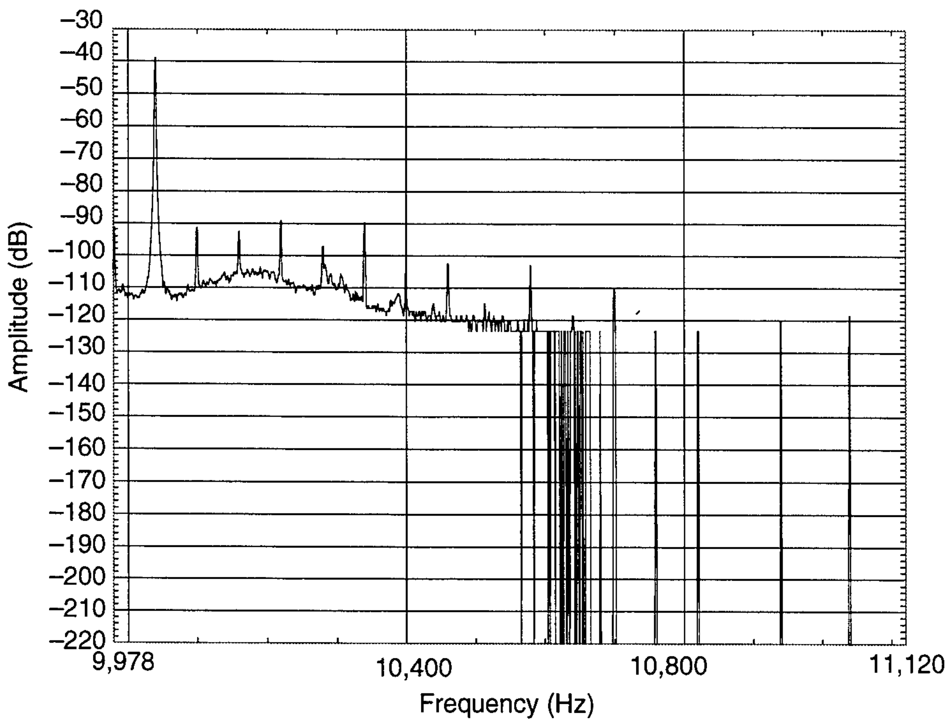


Figure C–75. Oscillator 96, 25 g at 1000 Hz, device horizontal, vertical vibration, $\gamma = 1.27 \times 10^{-8}/g$.

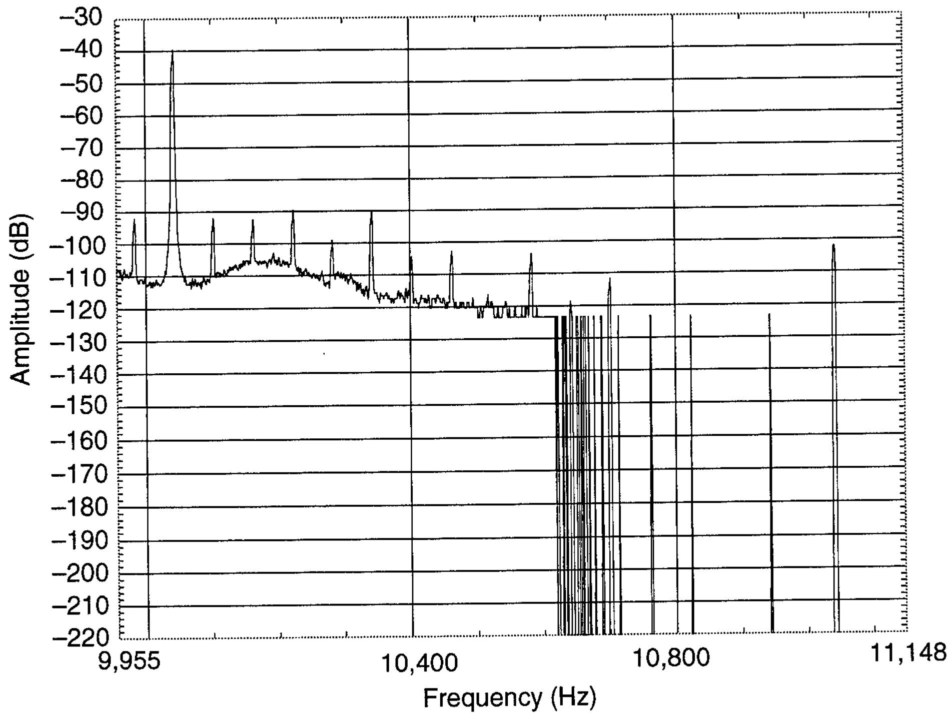


Figure C–76. Oscillator 96, 40 g at 1000 Hz, device horizontal, vertical vibration, $\gamma = 1.25 \times 10^{-8}/g$.

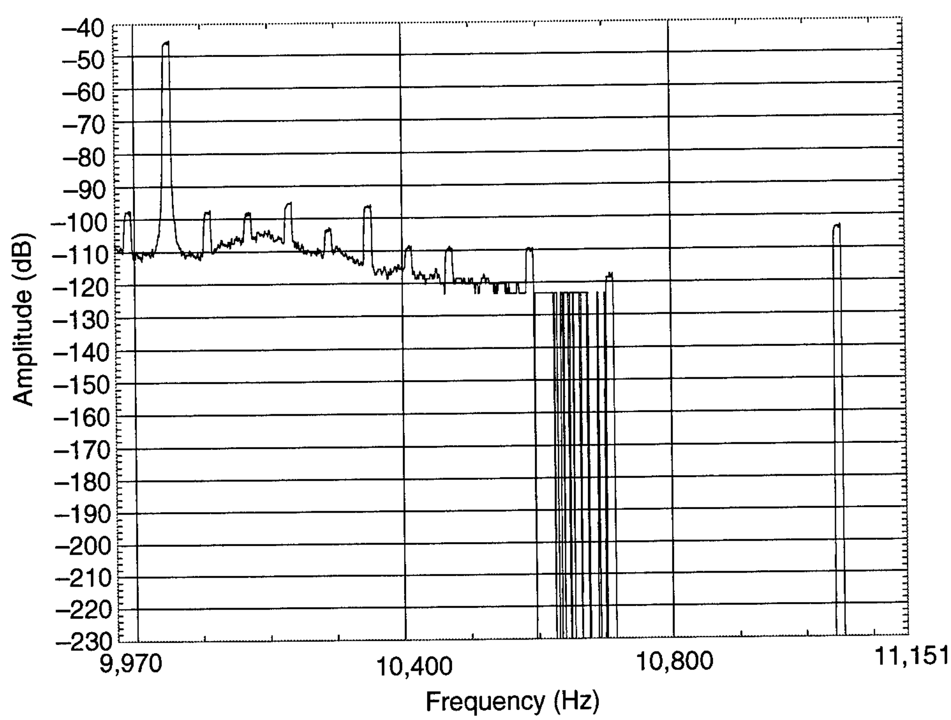


Figure C–77. Oscillator 96, 5 g at 2000 Hz, device horizontal, vertical vibration, $\gamma = 1.27 \times 10^{-8}/g$.

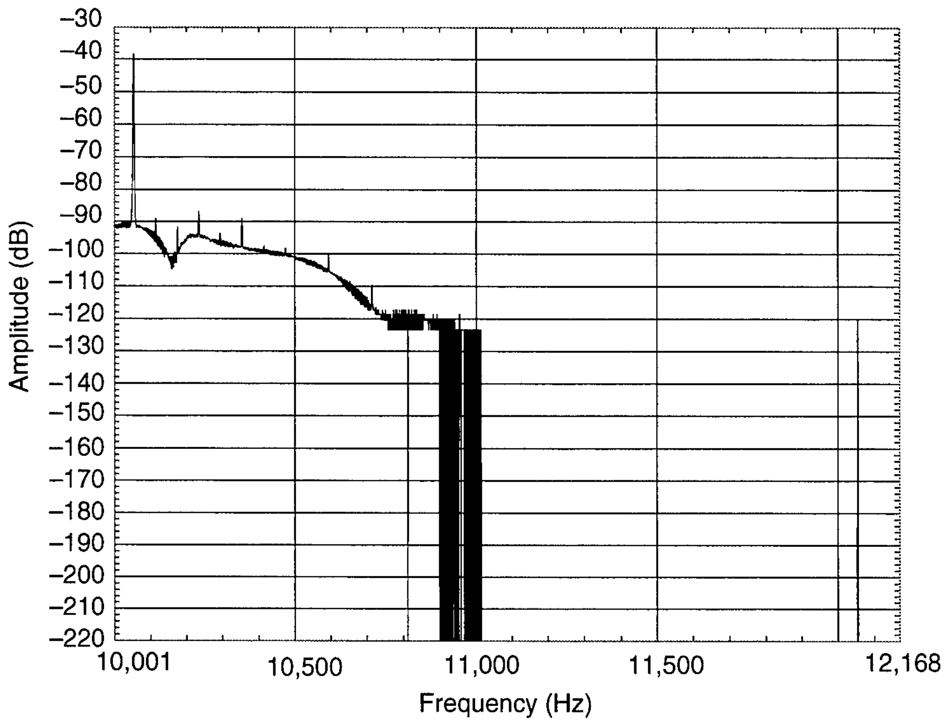


Figure C–78. Oscillator 96, 10 g at 2000 Hz, device horizontal, vertical vibration, $\gamma = 2.01 \times 10^{-8}/g$.

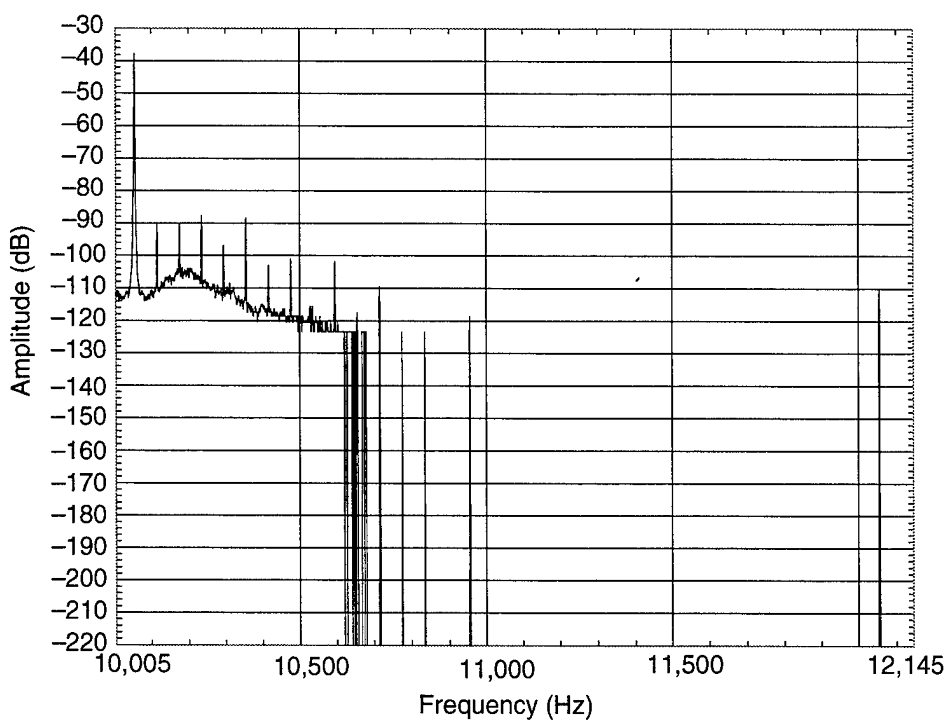


Figure C–79. Oscillator 96, 25 g at 2000 Hz, device horizontal, vertical vibration, $\gamma = 1.60 \times 10^{-8}/g$.

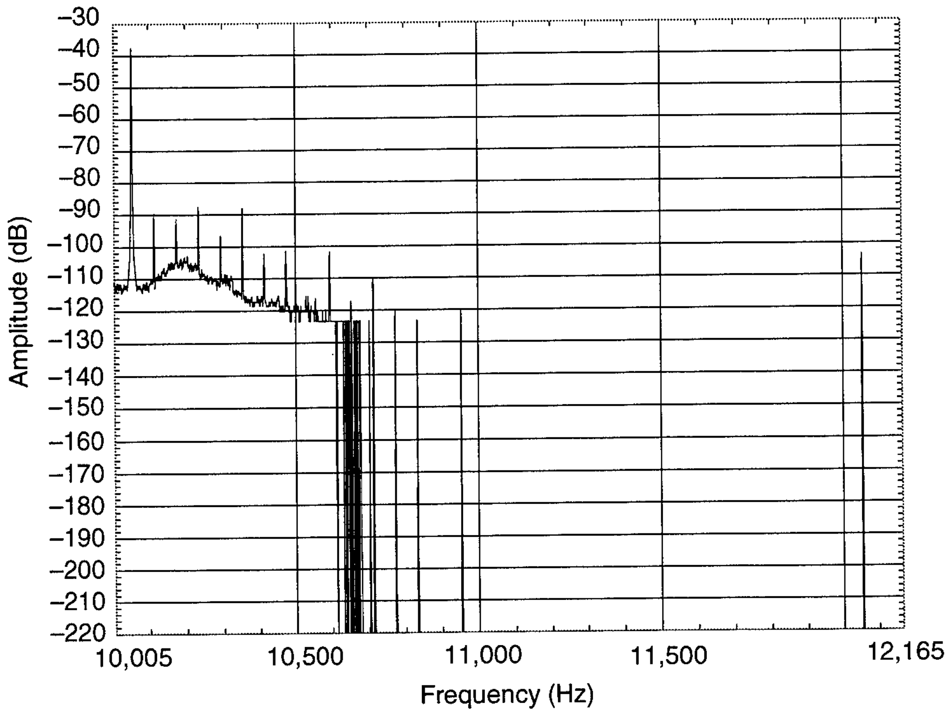
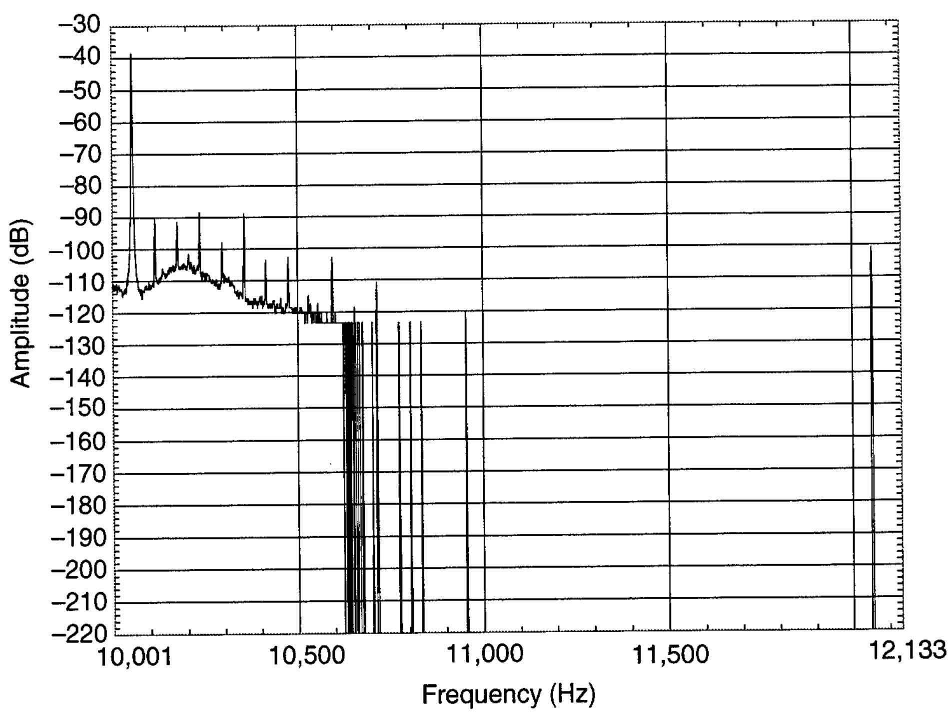


Figure C–80. Oscillator 96, 40 g at 2000 Hz, device horizontal, vertical vibration, $\gamma = 1.42 \times 10^{-8}/g$.



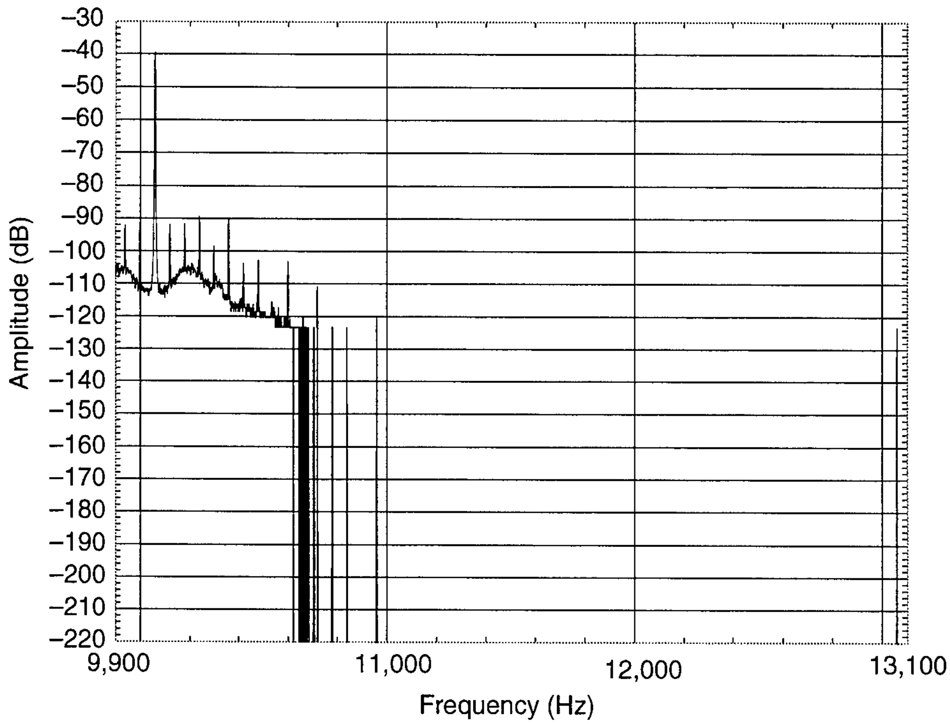


Figure C–81. Oscillator 96, 5 g at 3000 Hz, device horizontal, vertical vibration, $\gamma = 1.51 \times 10^{-8}/g$.

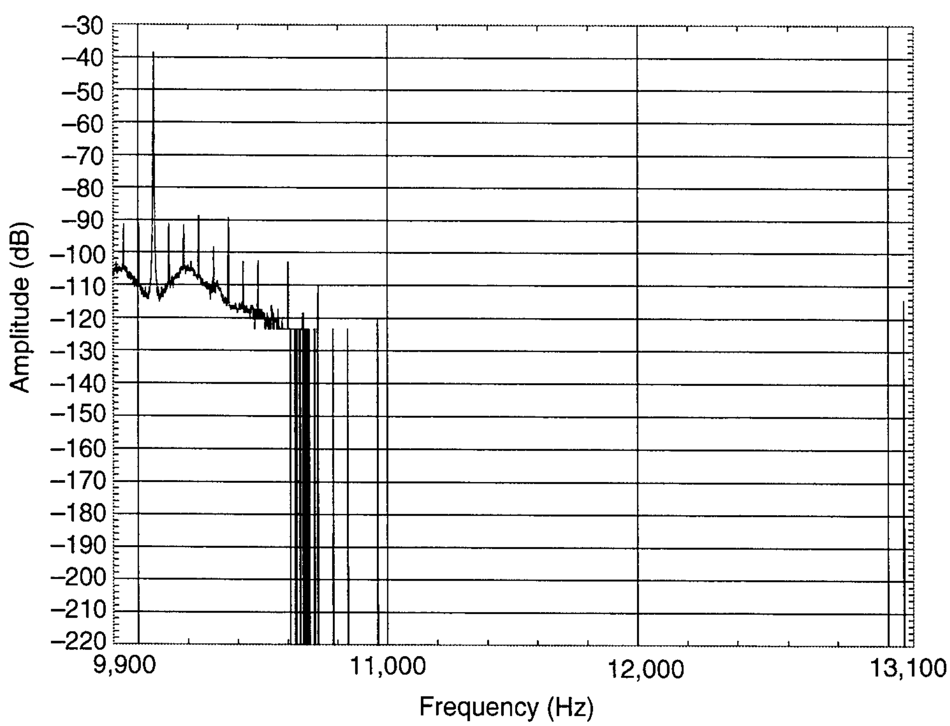


Figure C–82. Oscillator 96, 10 g at 3000 Hz, device horizontal, vertical vibration, $\gamma = 1.90 \times 10^{-8}/g$.

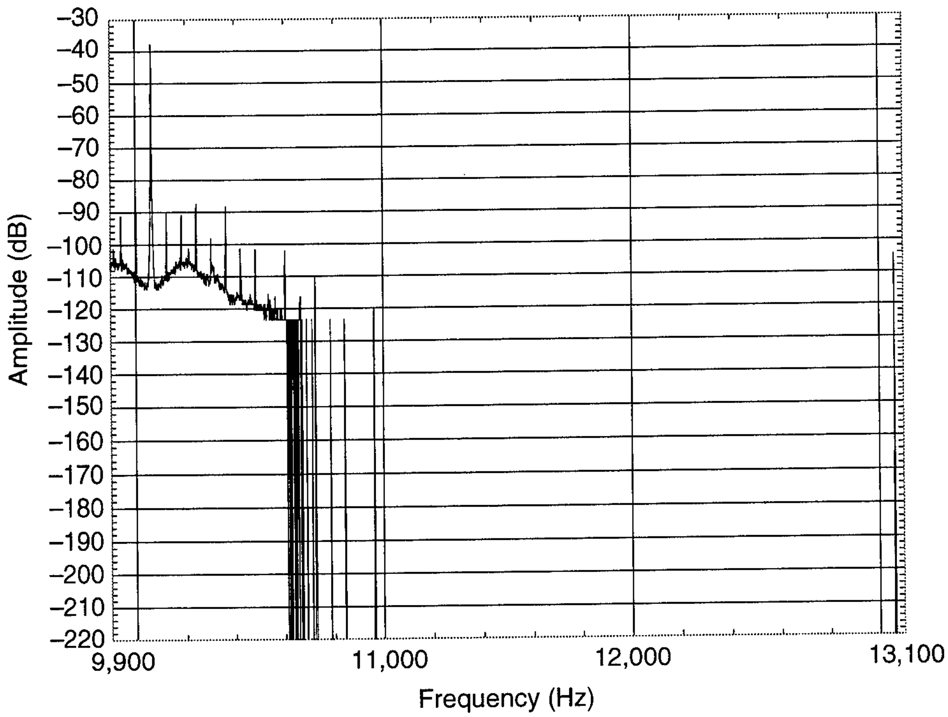


Figure C–83. Oscillator 96, 25 g at 3000 Hz, device horizontal, vertical vibration, $\gamma = 1.91 \times 10^{-8}/g$.

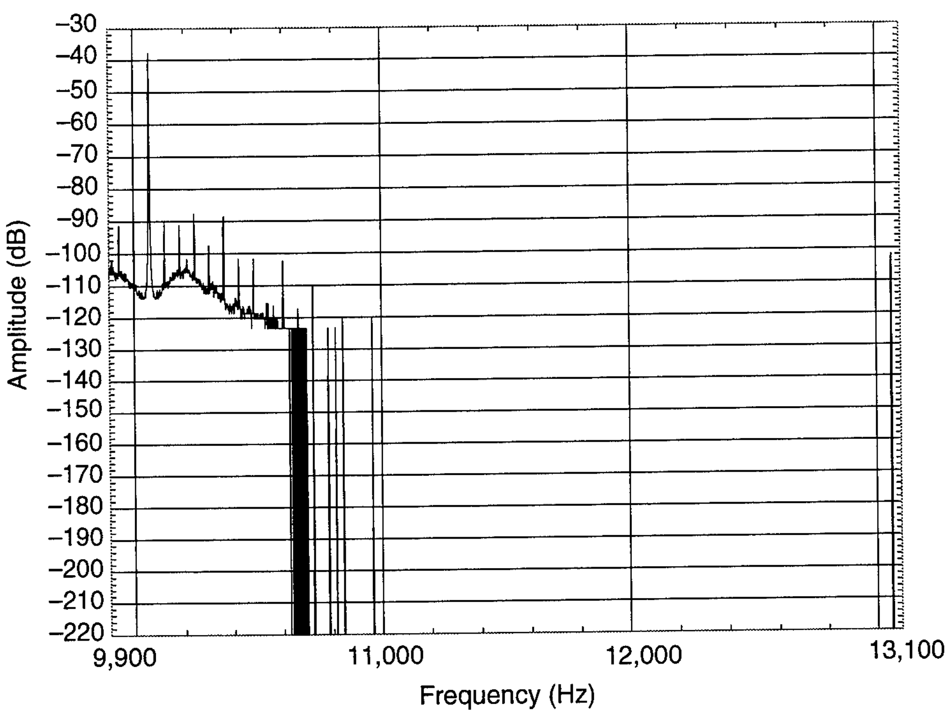


Figure C–84. Oscillator 96, 40 g at 3000 Hz, device horizontal, vertical vibration, $\gamma = 1.89 \times 10^{-8}/g$.

Figure C–85. Baseline measurement oscillator 74, screw up, vertical vibration.

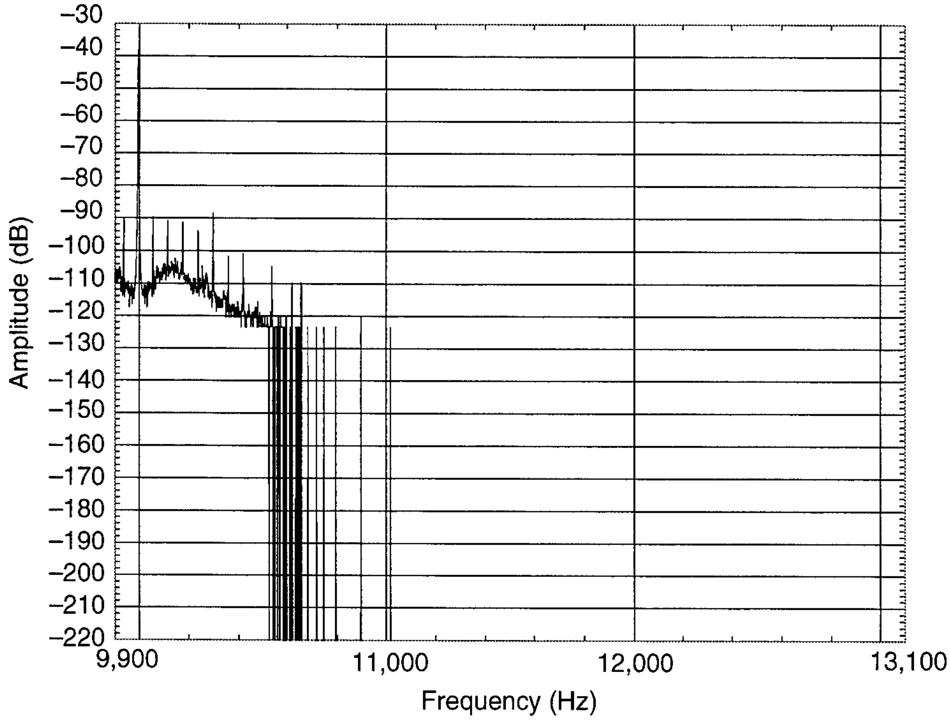


Figure C–86. Oscillator 74, 0.3 g at 5 Hz, screw up, vertical vibration, $\gamma = 9.94 \times 10^{-10}/g$.

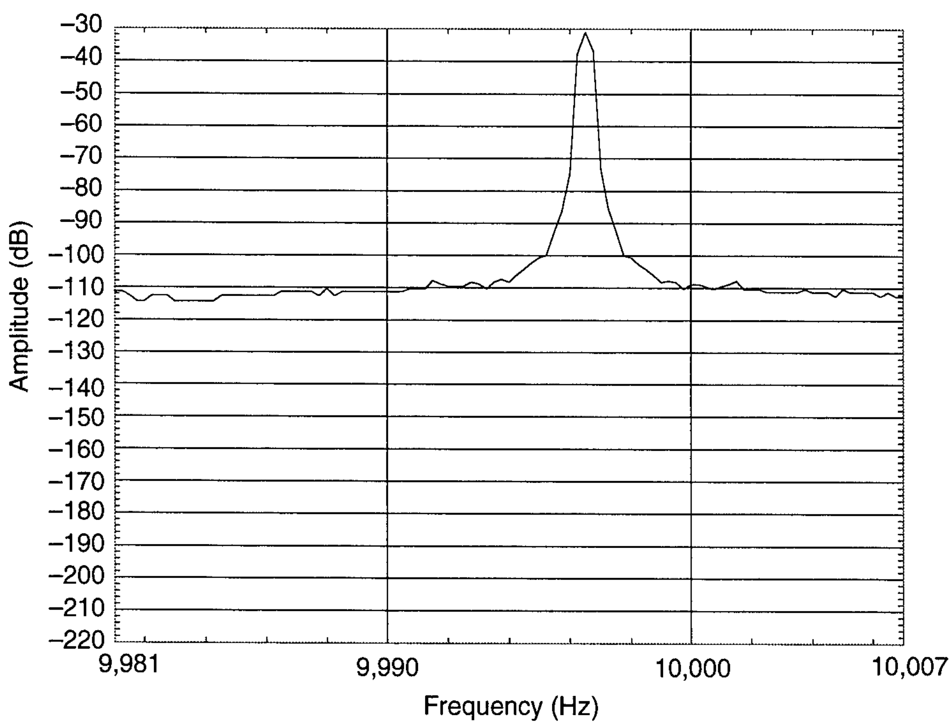


Figure C–87. Oscillator 74, 1 g at 25 Hz, screw up, vertical vibration, $\gamma = 2.82 \times 10^{-9}/g$.

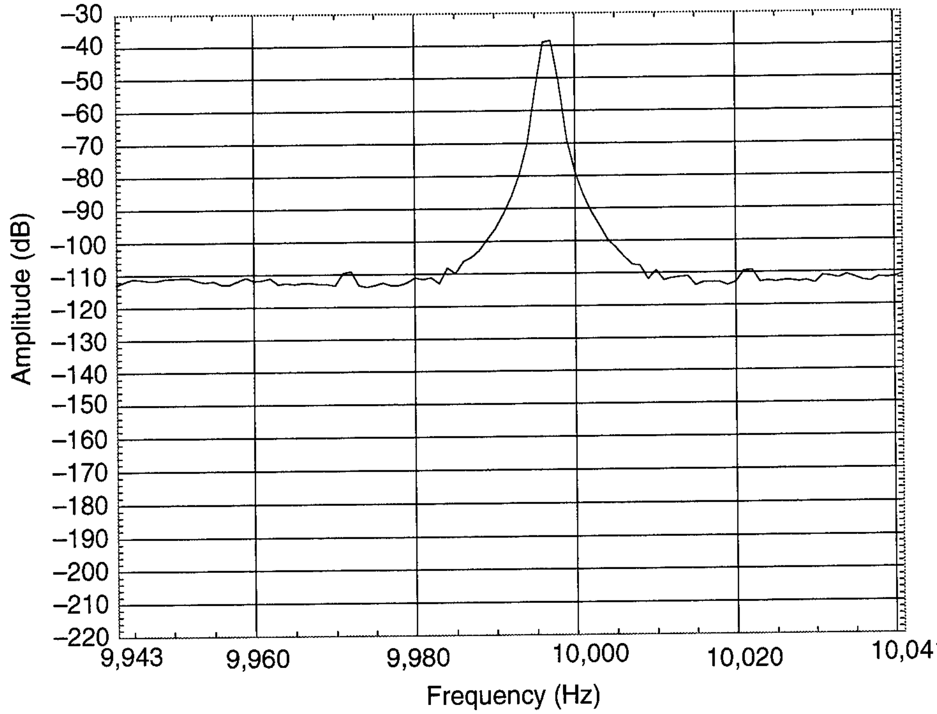


Figure C–88. Oscillator 74, 5 g at 25 Hz, screw up, vertical vibration, $\gamma = 1.59 \times 10^{-9}/g$.

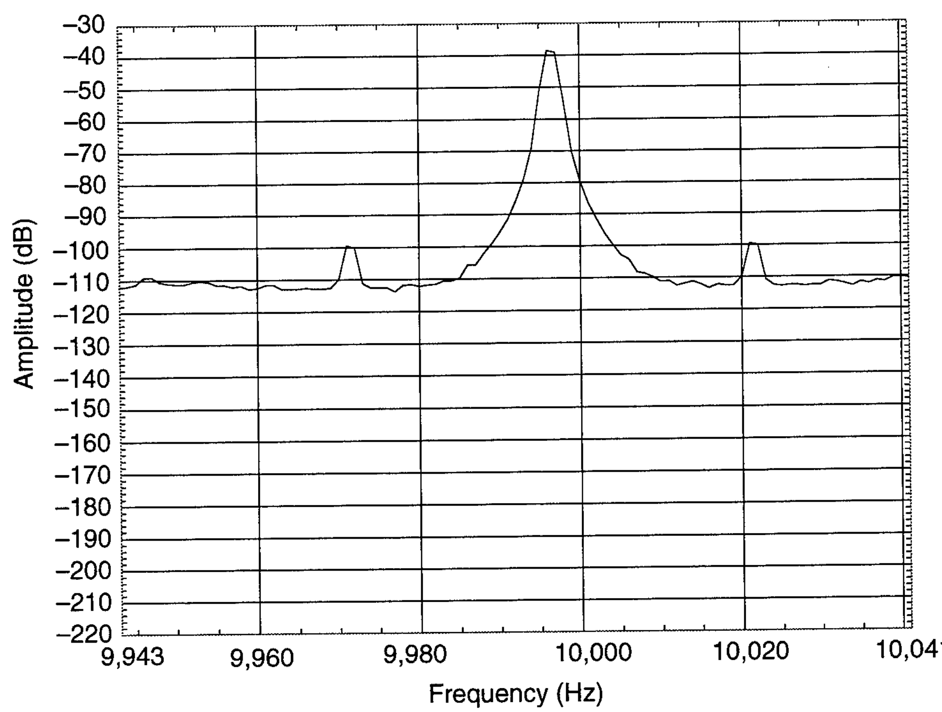


Figure C–89. Oscillator 74, 8 g at 25 Hz, screw up, vertical vibration, $\gamma = 1.40 \times 10^{-9}/g$.

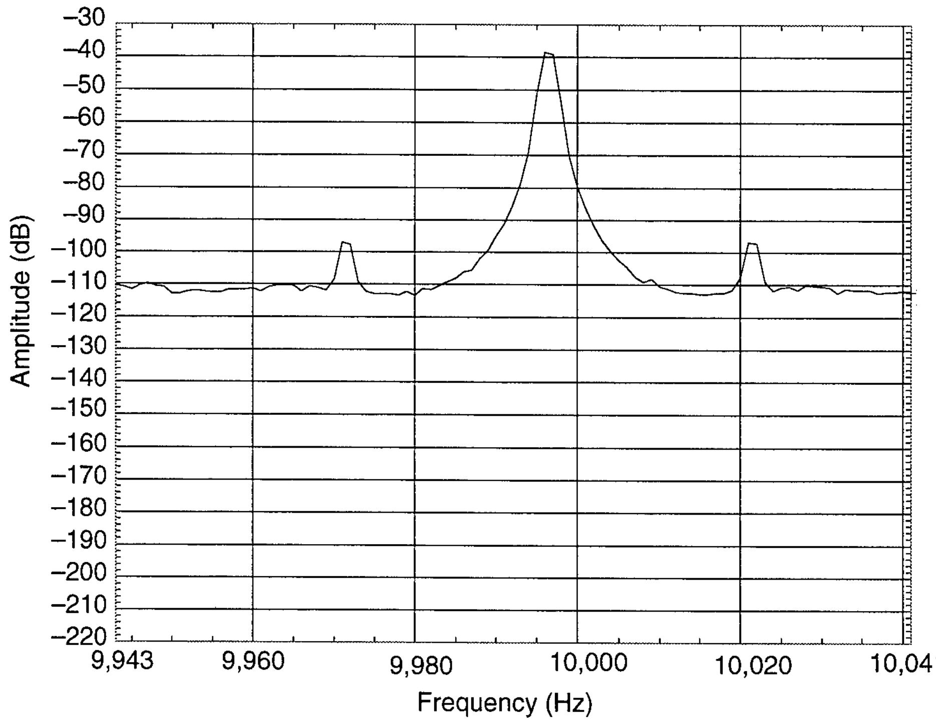


Figure C–90. Oscillator 74, 1 g at 50 Hz, screw up, vertical vibration, No Signal.

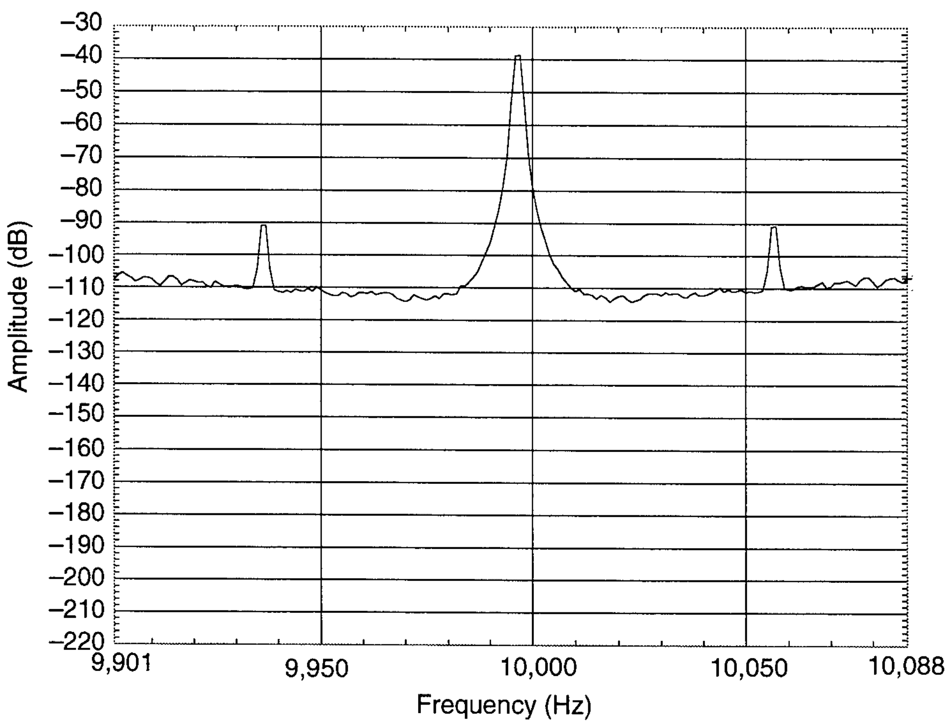


Figure C–91. Oscillator 74, 5 g at 50 Hz, screw up, vertical vibration, $\gamma = 4.49 \times 10^{-9}/g$.

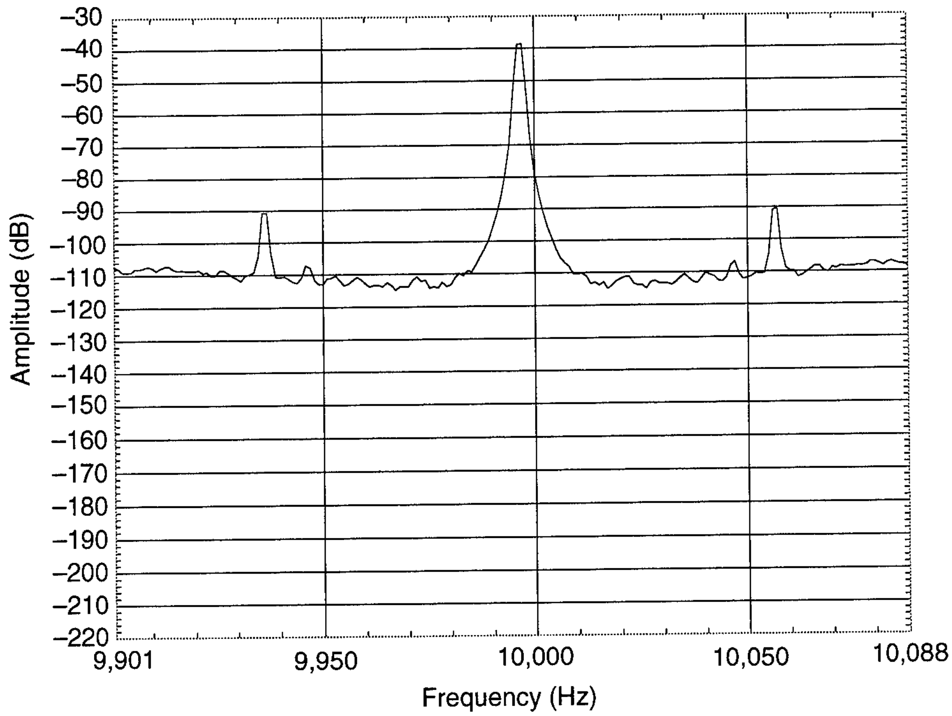


Figure C–92. Oscillator 74, 10 g at 50 Hz, screw up, vertical vibration, $\gamma = 1.42 \times 10^{-9}/g$.

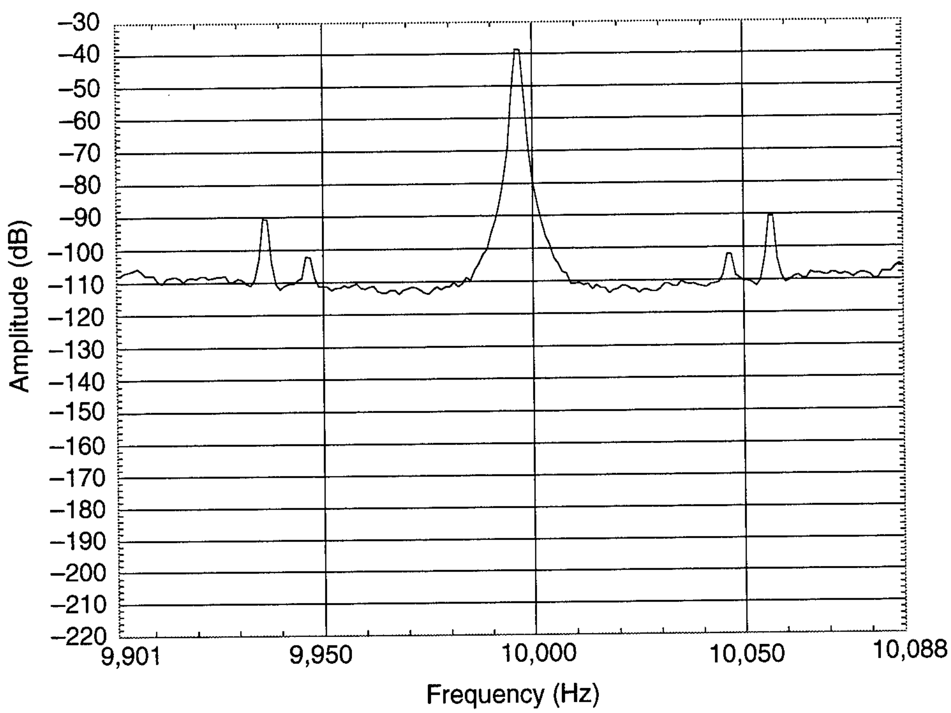


Figure C–93. Oscillator 74, 25 g at 50 Hz, screw up, vertical vibration, $\gamma = 1.01 \times 10^{-9}/g$.

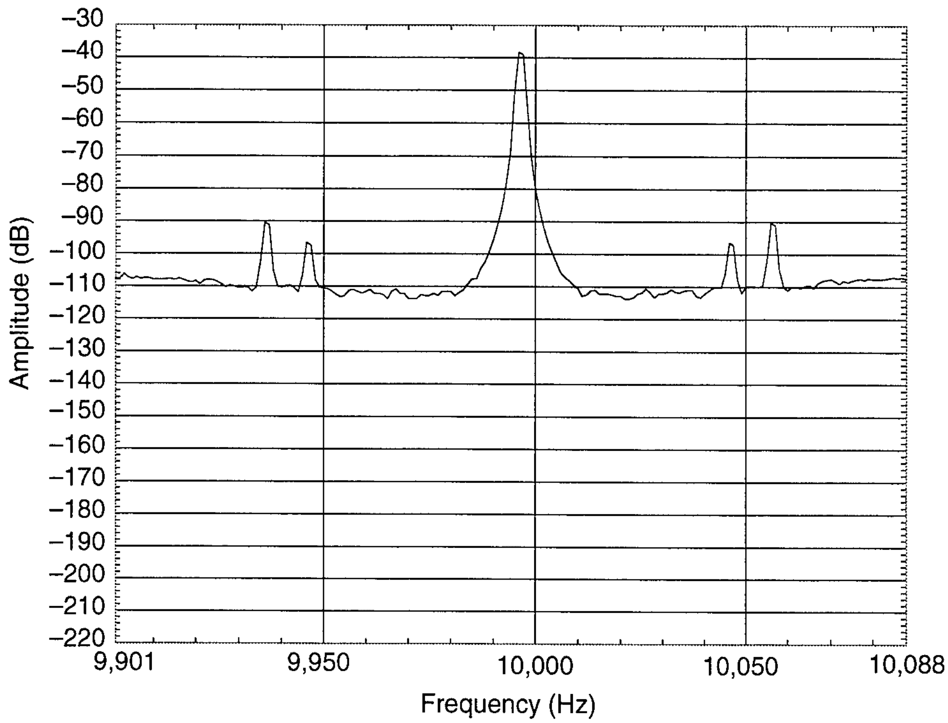


Figure C–94. Oscillator 74, 31.9 g at 50 Hz, screw up, vertical vibration, $\gamma = 9.94 \times 10^{-10}/g$.

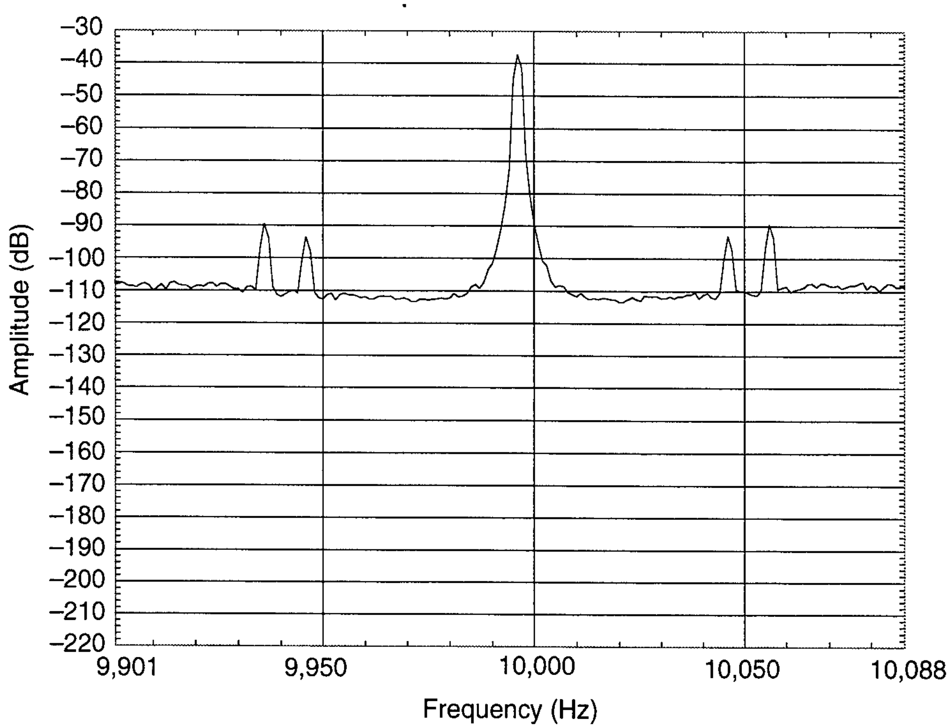


Figure C–95. Oscillator 74, 1 g at 500 Hz, screw up, vertical vibration, No Signal.

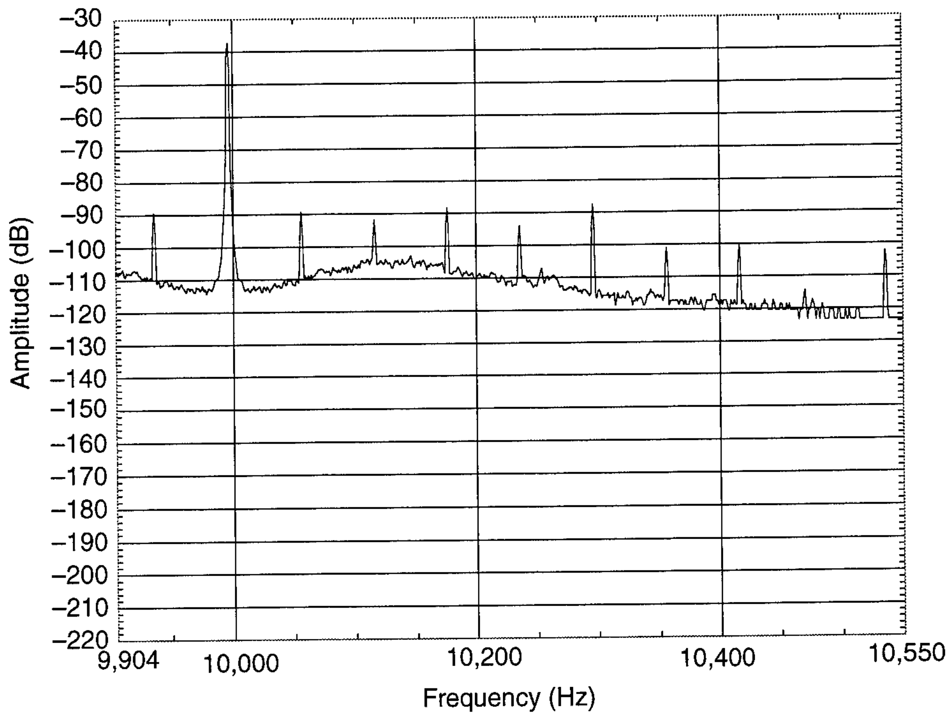


Figure C–96. Oscillator 74, 5 g at 500 Hz, screw up, vertical vibration, $\gamma = 6.34 \times 10^{-9}/g$.

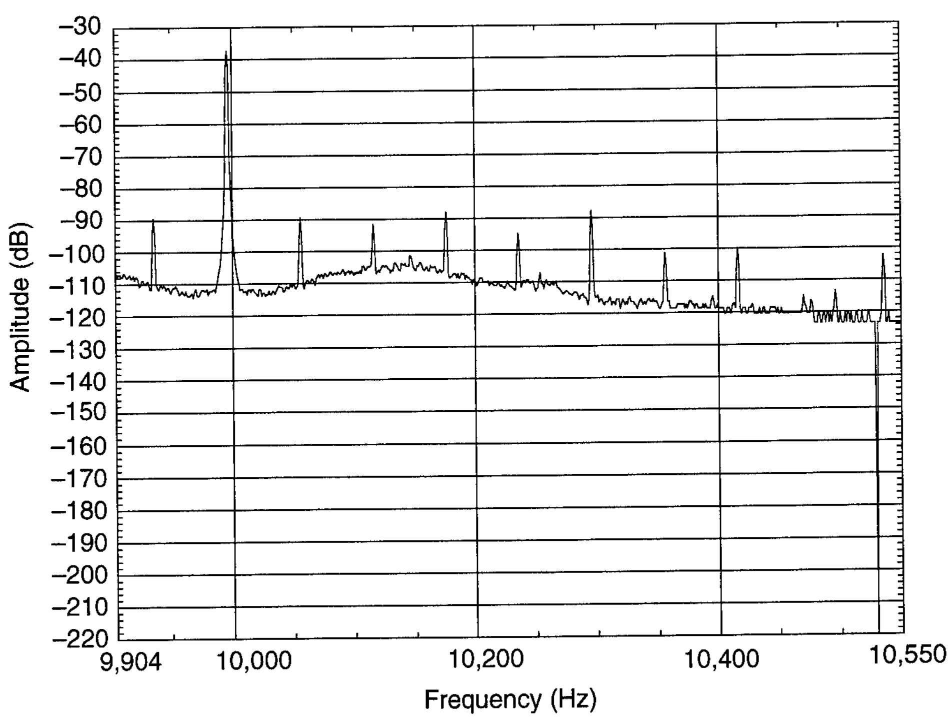


Figure C–97.
Oscillator 74, 10 g at 500 Hz, screw up, vertical vibration, $\gamma = 3.56 \times 10^{-9}/g$.

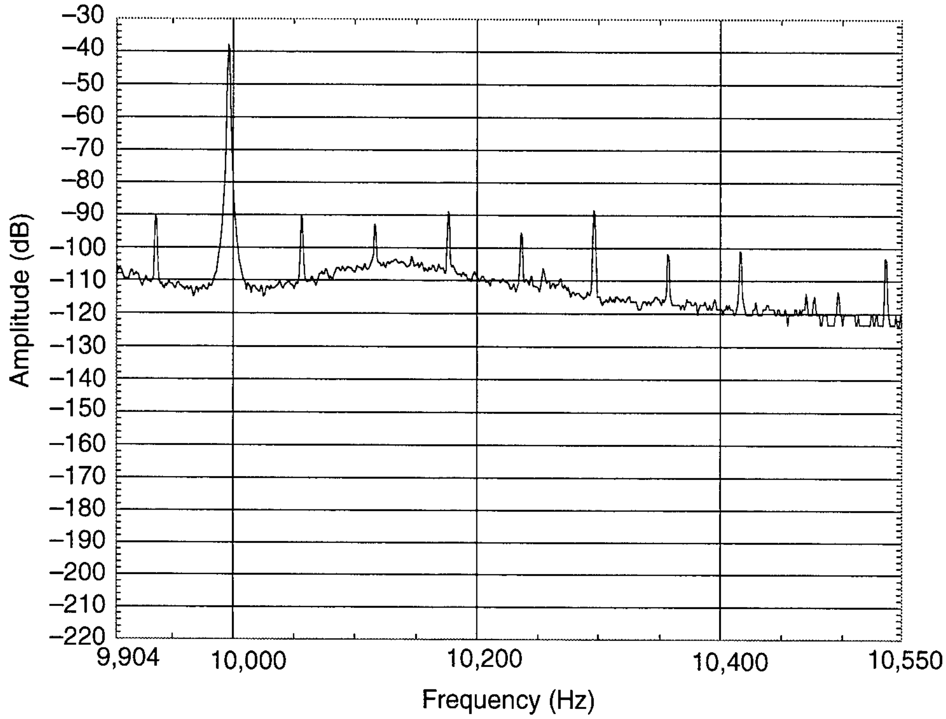


Figure C–98.
Oscillator 74, 25 g at 500 Hz, screw up, vertical vibration, $\gamma = 2.53 \times 10^{-9}/g$.

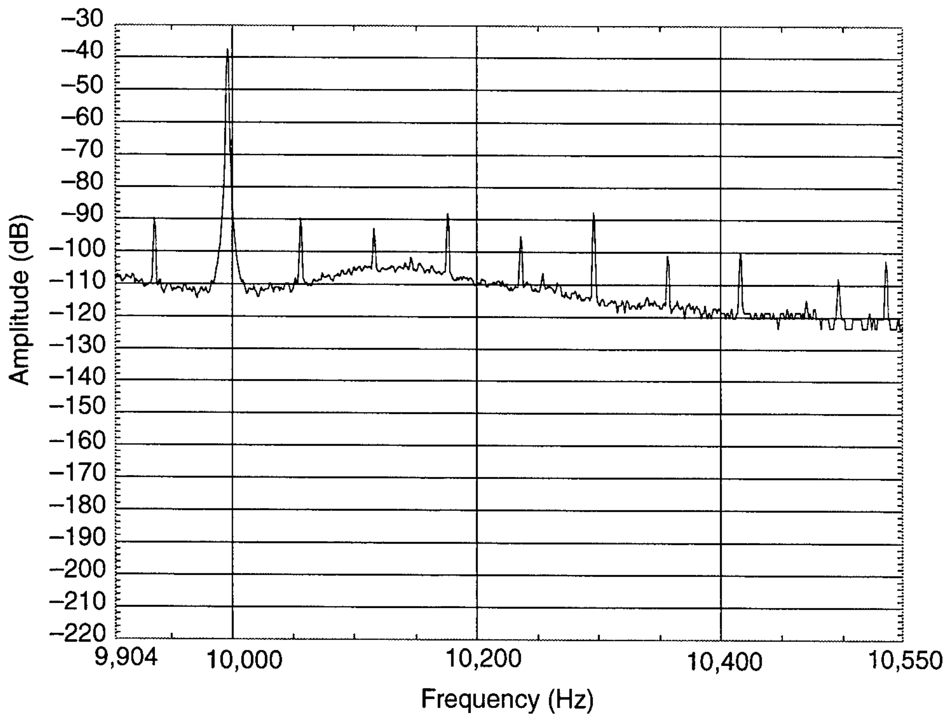


Figure C–99. Oscillator 74, 40 g at 500 Hz, screw up, vertical vibration, $\gamma = 2.51 \times 10^{-9}$/g.

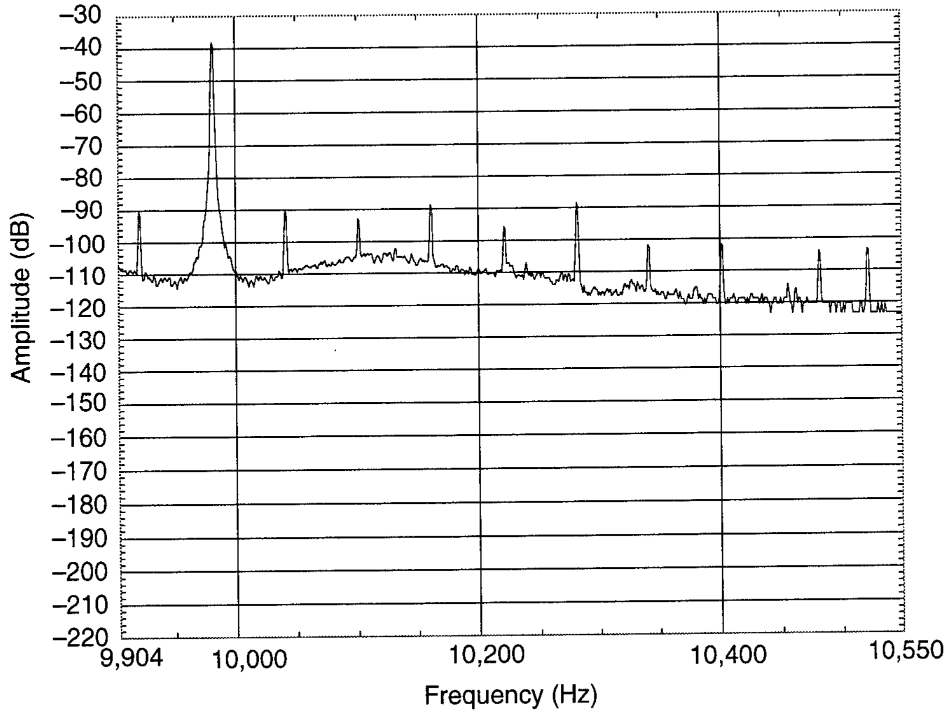


Figure C–100. Oscillator 74, 5 g at 1000 Hz, screw up, vertical vibration, 1.79×10^{-8}/g.

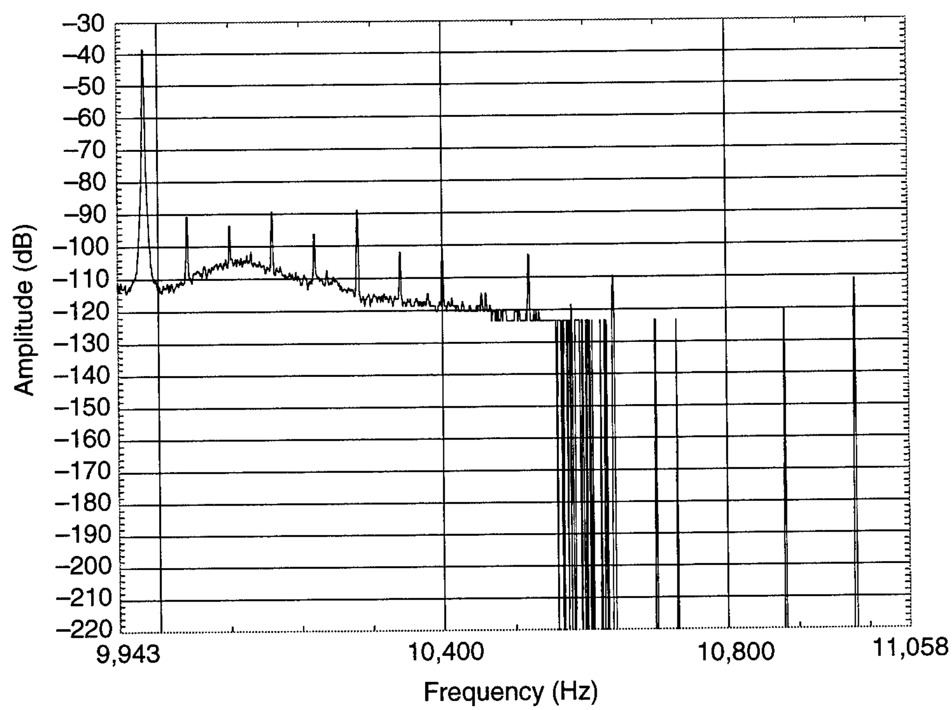


Figure C–101. Oscillator 74, 10 g at 1000 Hz, screw up, vertical vibration, $\gamma = 8.95 \times 10^{-9}/g$.

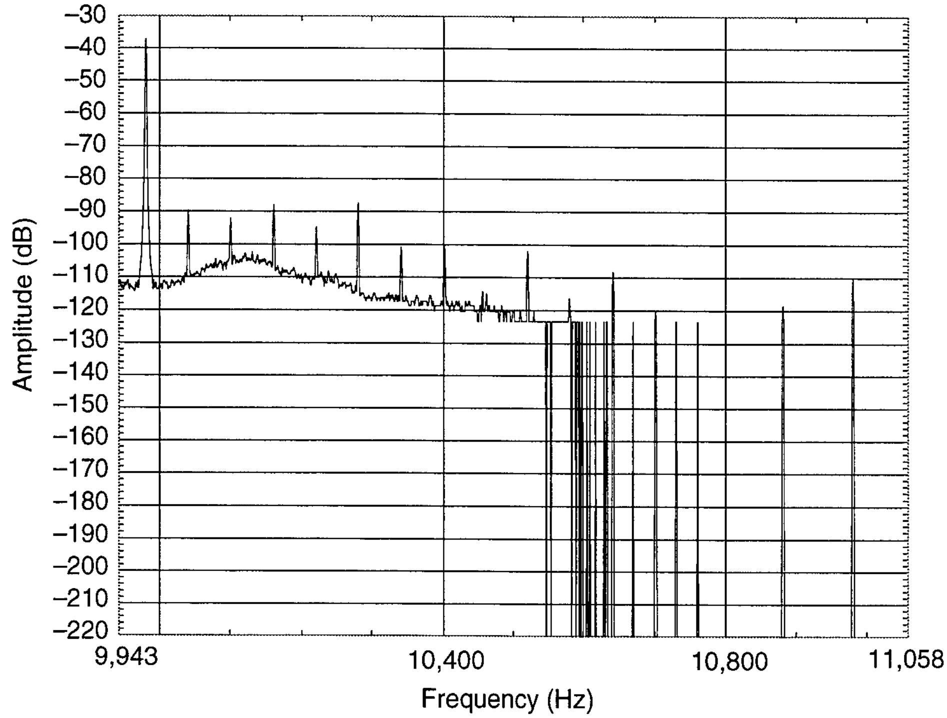
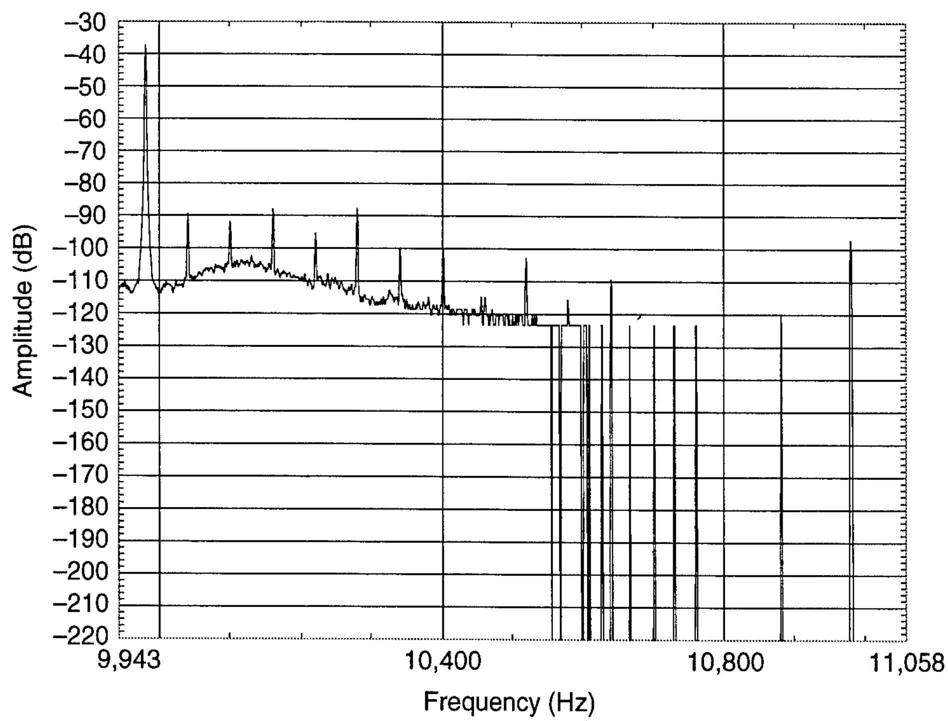


Figure C–102. Oscillator 74, 25 g at 1000 Hz, screw up, vertical vibration, $\gamma = 1.60 \times 10^{-8}/g$.



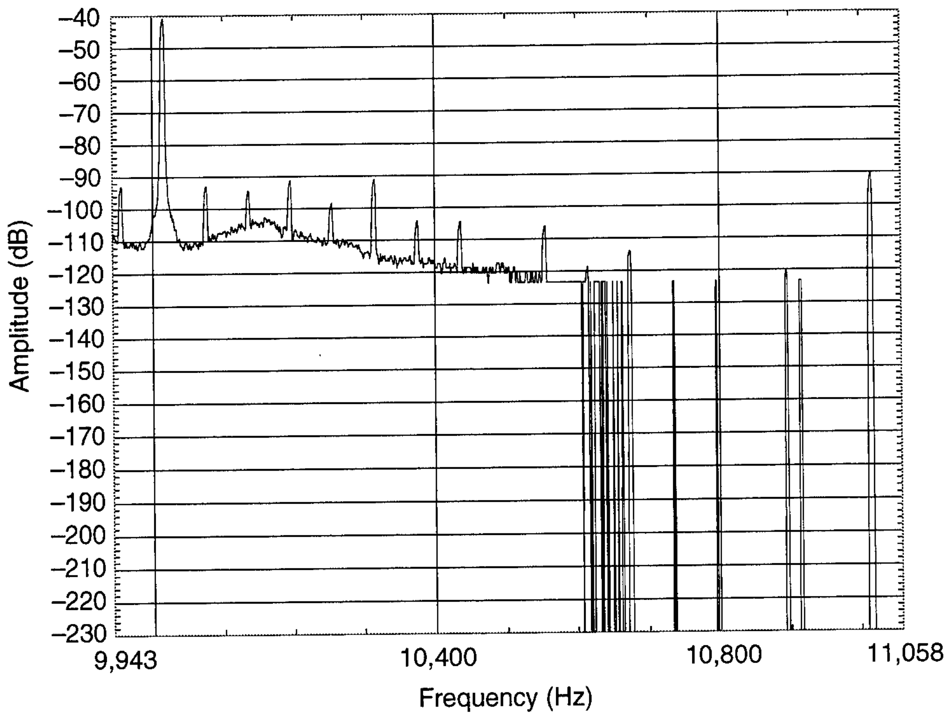


Figure C–103. Oscillator 74, 40 g at 1000 Hz, screw up, vertical vibration, $\gamma = 3.98 \times 10^{-8}/g$.

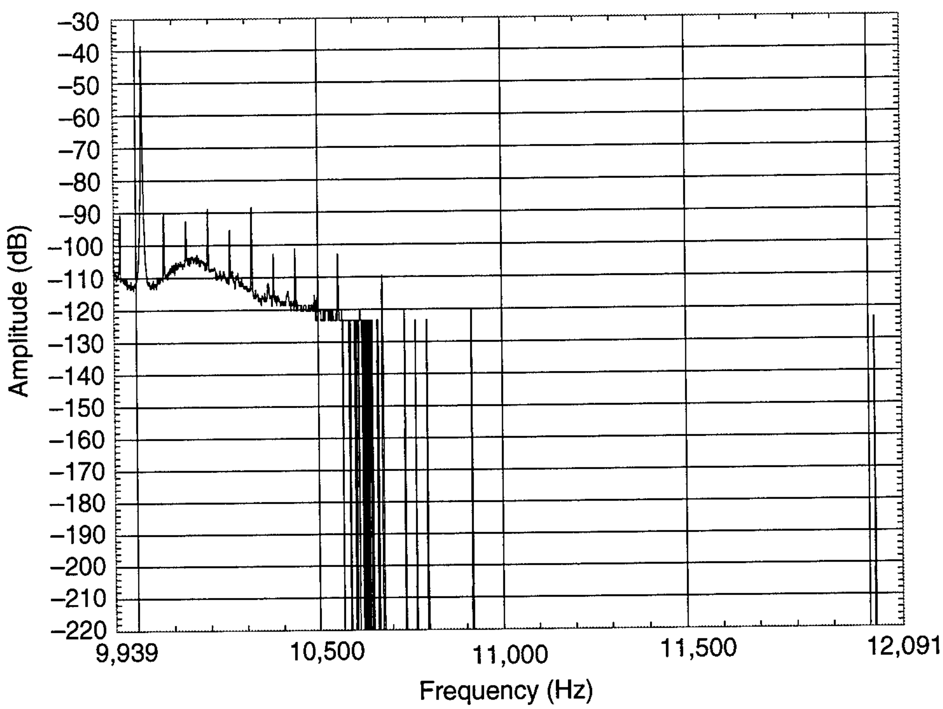


Figure C–104. Oscillator 74, 5 g at 2000 Hz, screw up, vertical vibration, $\gamma = 9.00 \times 10^{-9}/g$.

Figure C–105. Oscillator 74, 10 g at 2000 Hz, screw up, vertical vibration, $\gamma = 8.98 \times 10^{-9}/g$.

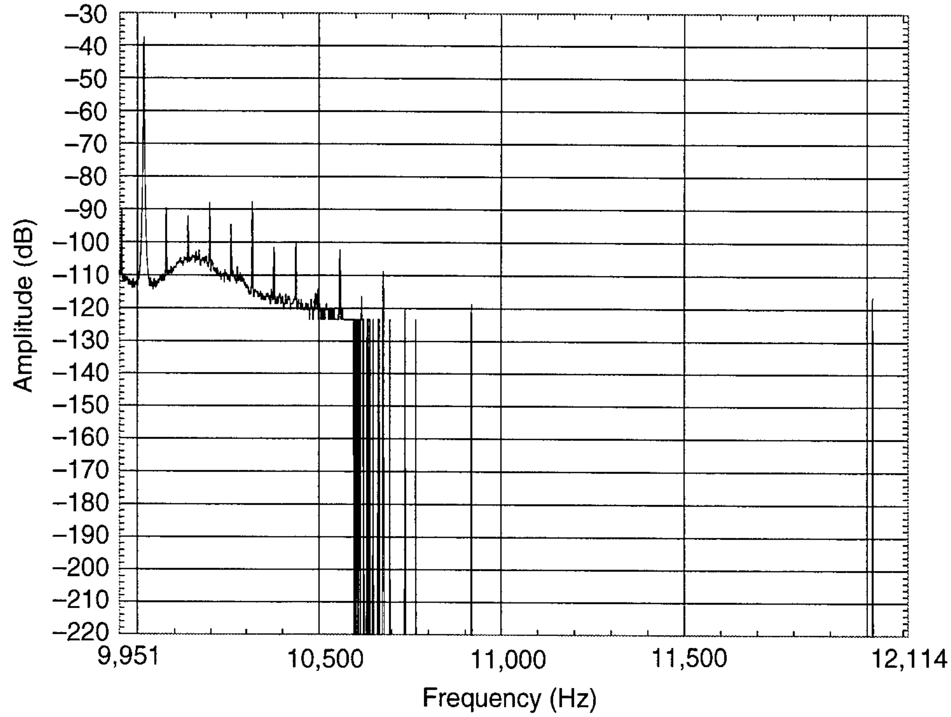


Figure C–106. Oscillator 74, 25 g at 2000 Hz, screw up, vertical vibration, $\gamma = 1.27 \times 10^{-8}/g$.

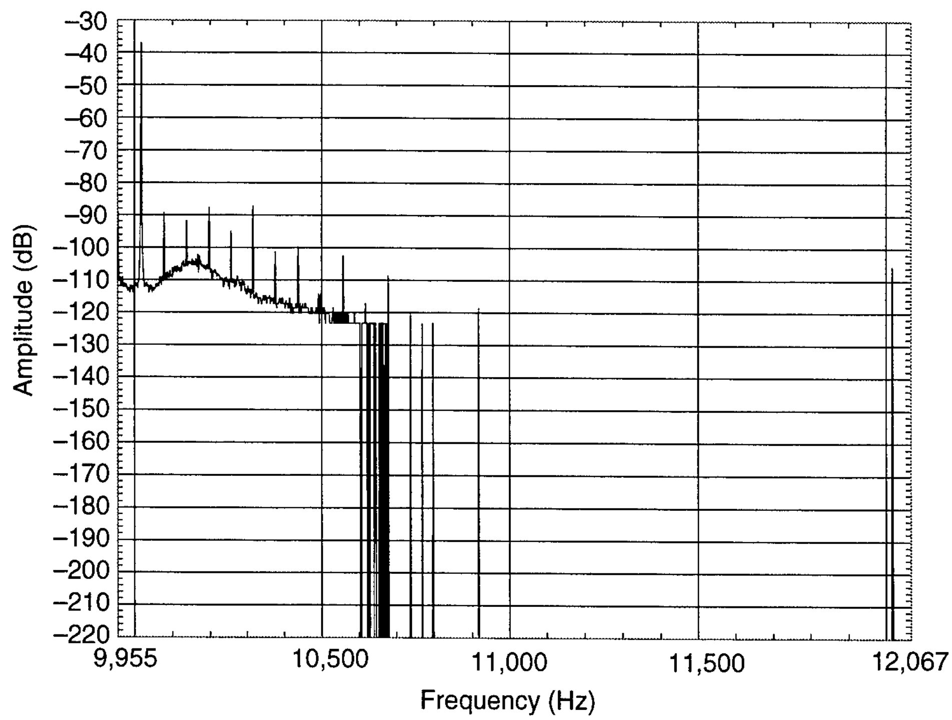


Figure C–107. Oscillator 74, 40 g at 2000 Hz, screw up, vertical vibration, $\gamma = 8.93 \times 10^{-9}$/g.

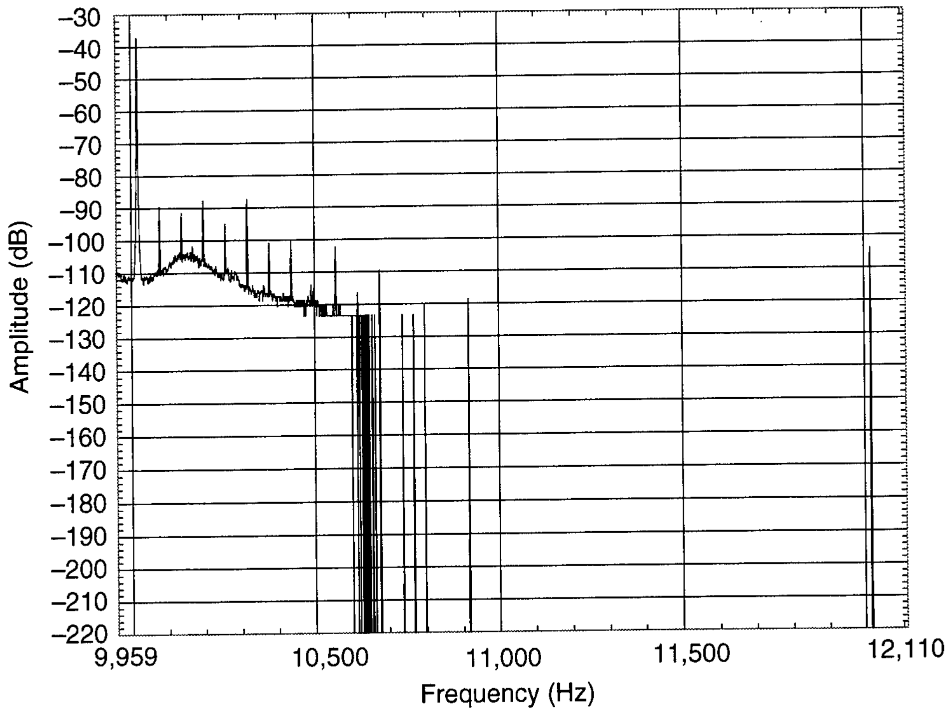


Figure C–108. Oscillator 74, 5 g at 3000 Hz, screw up, vertical vibration, $\gamma = 1.70 \times 10^{-7}$/g.

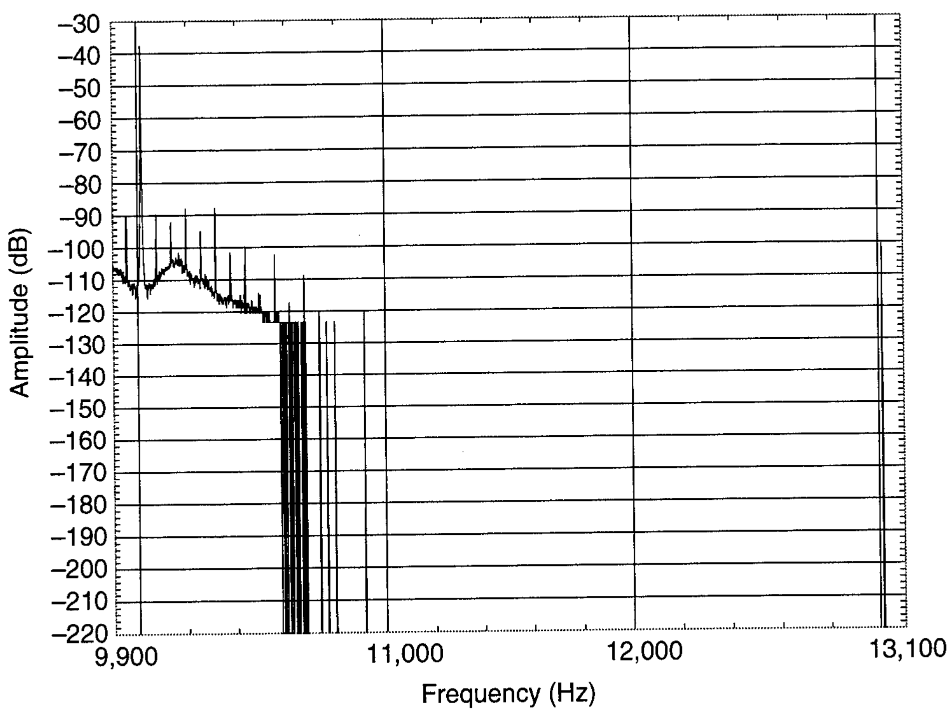


Figure C–109.
Oscillator 74, 10 g at 3000 Hz, screw up, vertical vibration, $\gamma = 2.13 \times 10^{-7}/g$.

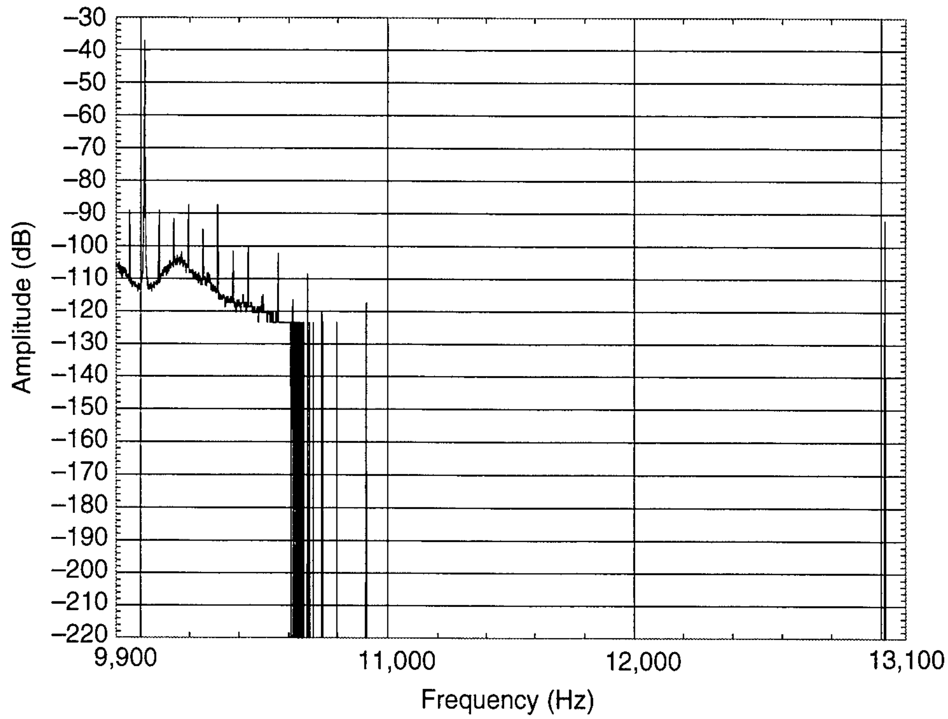


Figure C-110.
Oscillator 74, 25 g at 3000 Hz, screw up, vertical vibration, $\gamma = 1.52 \times 10^{-7}/g$.

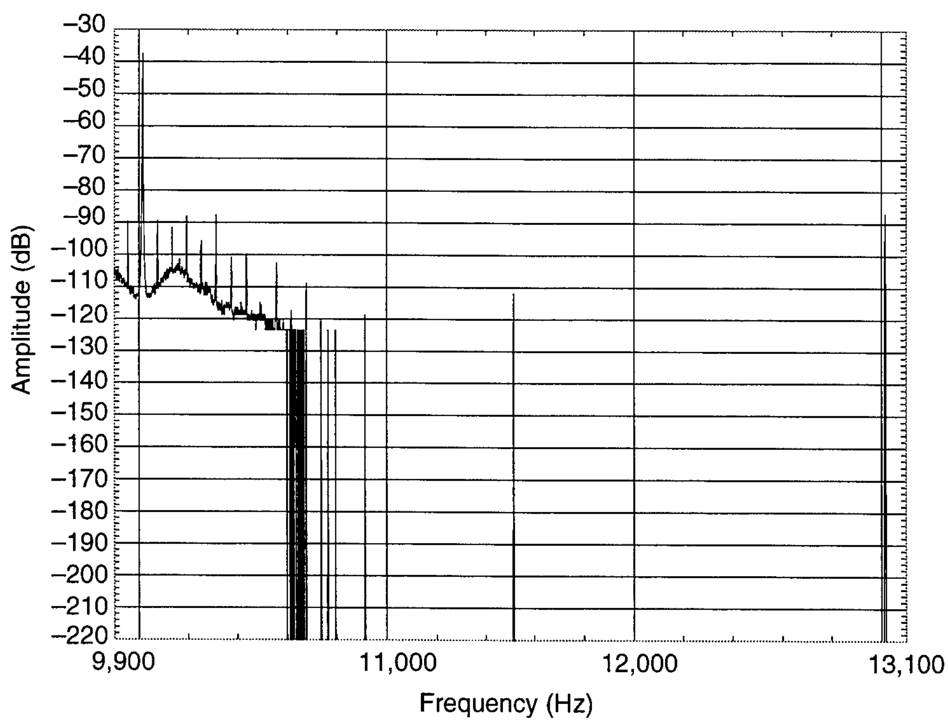


Figure C-111. Oscillator 74, 40 g at 3000 Hz, screw up, vertical vibration, $\gamma = 9.49 \times 10^{-8}/g$.

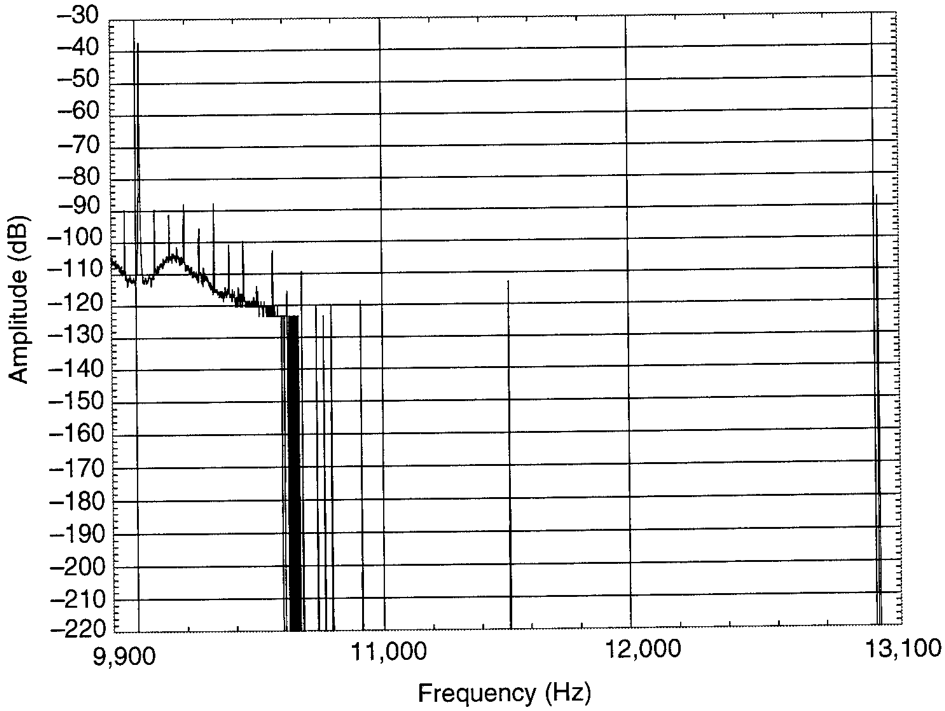


Figure C-112. Baseline measurement oscillator 74, screw sideways, vertical vibration.

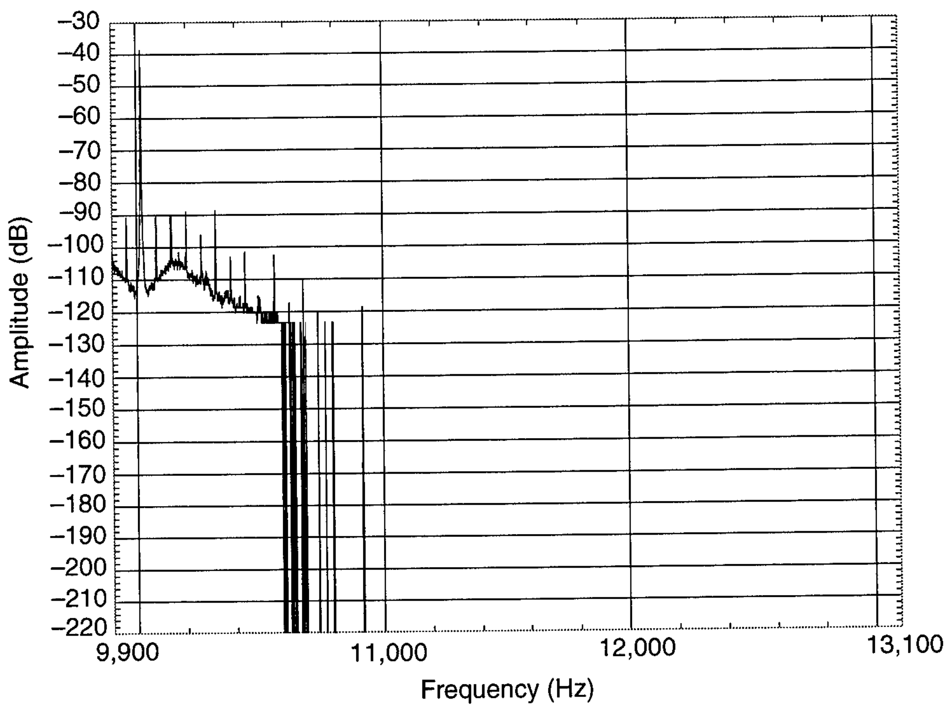


Figure C-113. Oscillator 74, 0.3 g at 5 Hz, screw sideways, vertical vibration, $\gamma = 1.18 \times 10^{-9}/g$.

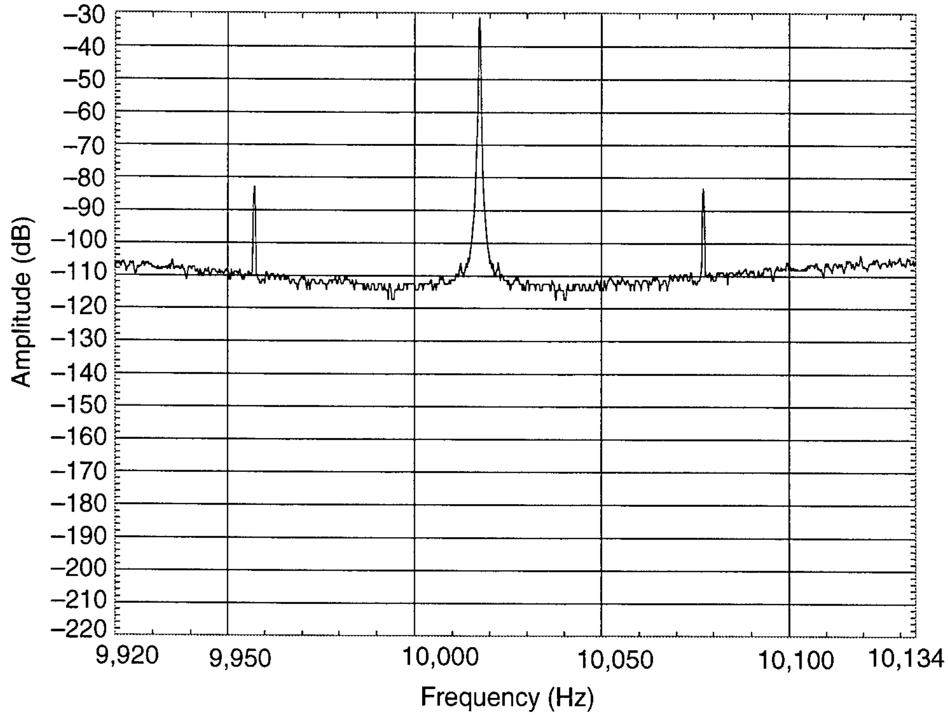
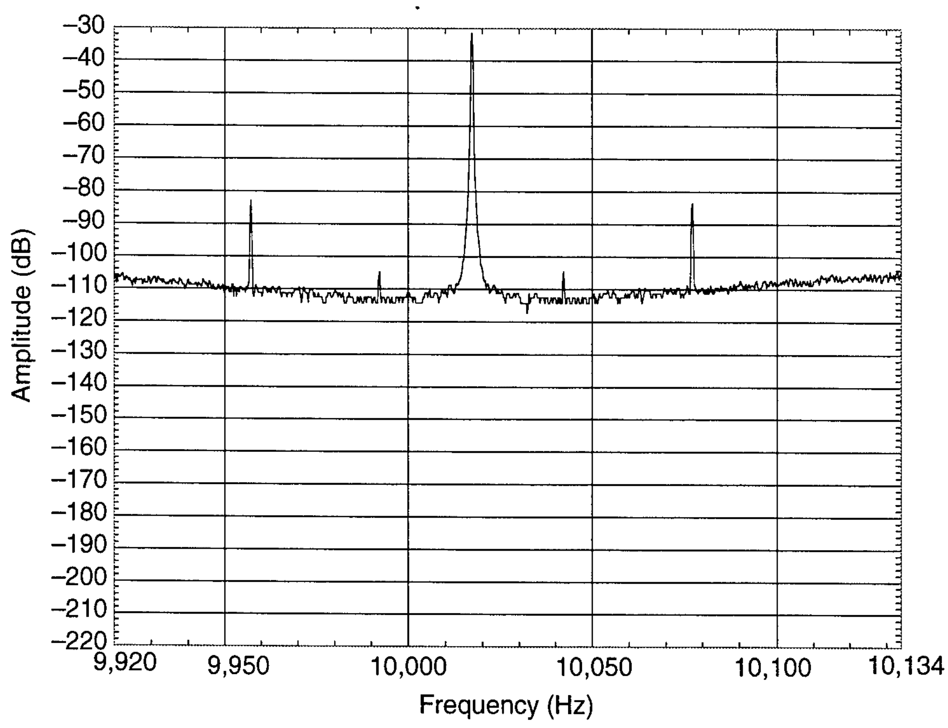


Figure C-114. Oscillator 74, 1 g at 25 Hz, screw sideways, vertical vibration, $\gamma = 2.24 \times 10^{-8}/g$.



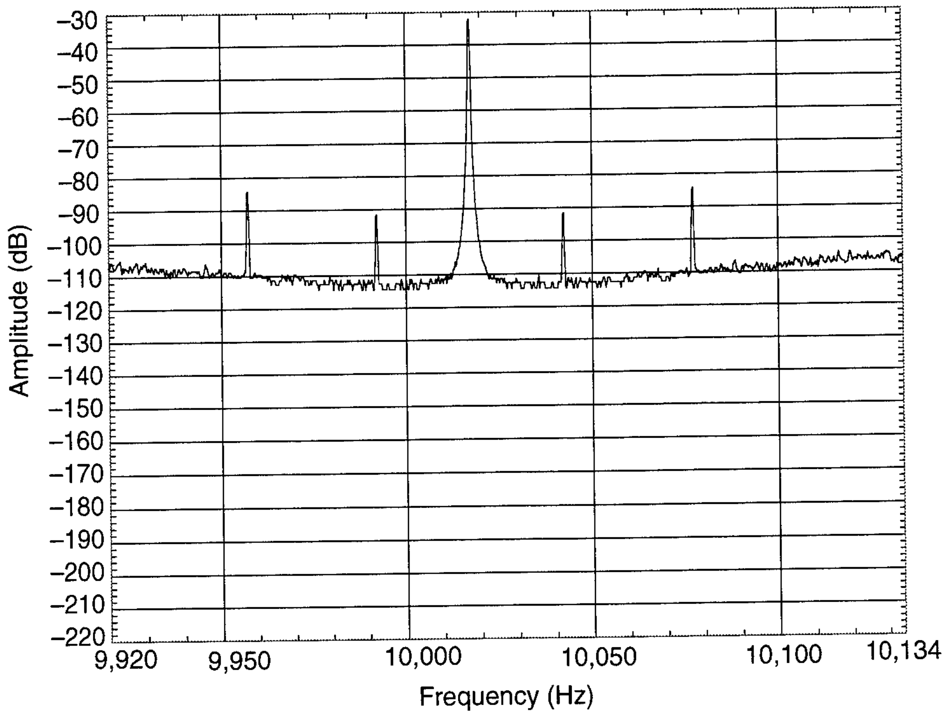


Figure C-115. Oscillator 74, 5 g at 25 Hz, screw sideways, vertical vibration, $\gamma = 2.24 \times 10^{-8}/g$.

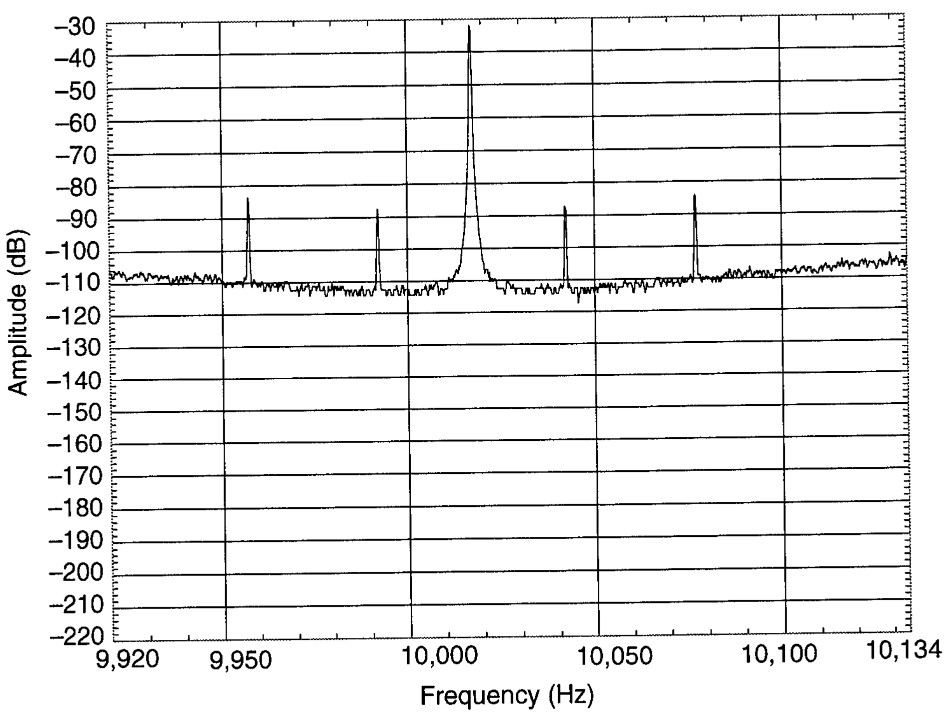


Figure C-116. Oscillator 74, 8 g at 25 Hz, screw sideways, vertical vibration, $\gamma = 1.40 \times 10^{-9}/g$.

Figure C-117. Oscillator 74, 1 g at 50 Hz, screw sideways, vertical vibration, No Signal.

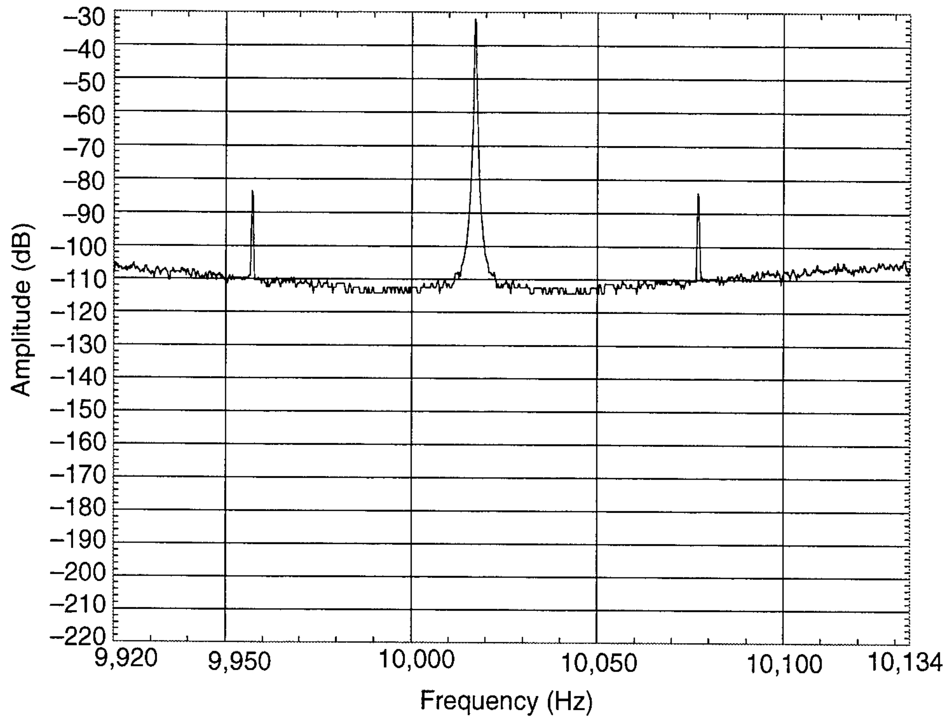


Figure C-118. Oscillator 74, 5 g at 50 Hz, screw sideways, vertical vibration, $\gamma = 1.59 \times 10^{-9}/g$.

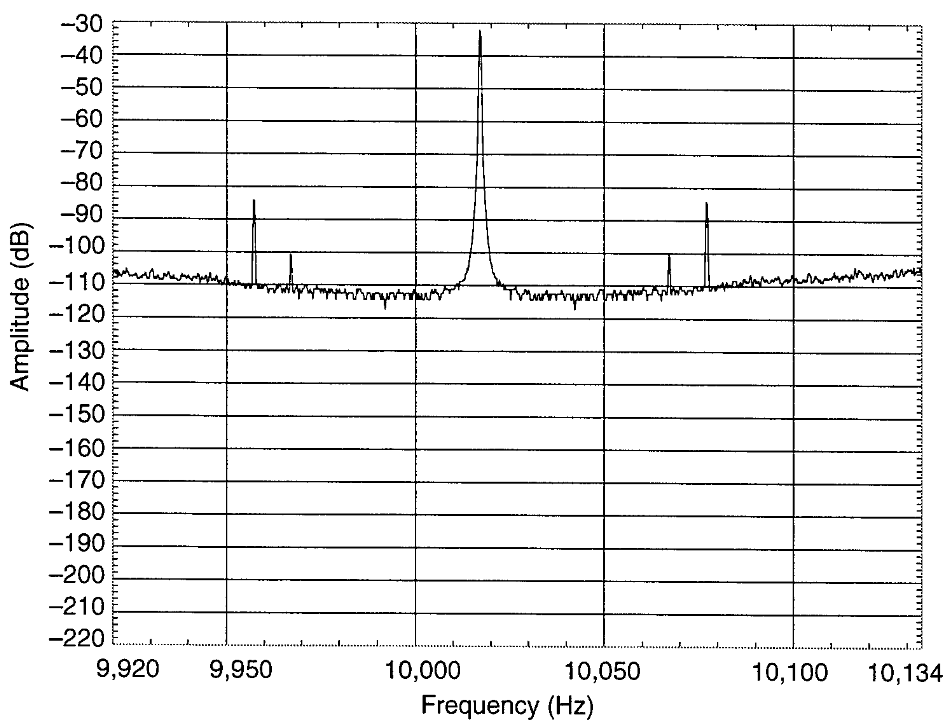


Figure C-119. Oscillator 74, 10 g at 50 Hz, screw sideways, vertical vibration, $\gamma = 1.78 \times 10^{-9}$/g.

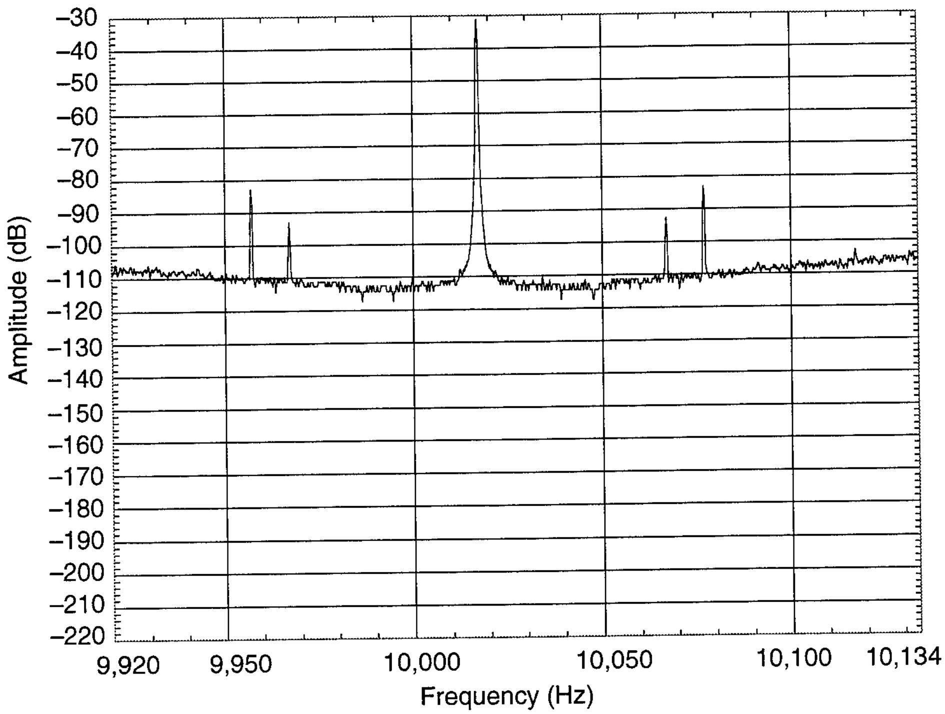


Figure C-120. Oscillator 74, 25 g at 50 Hz, screw sideways, vertical vibration, $\gamma = 1.79 \times 10^{-9}$/g.

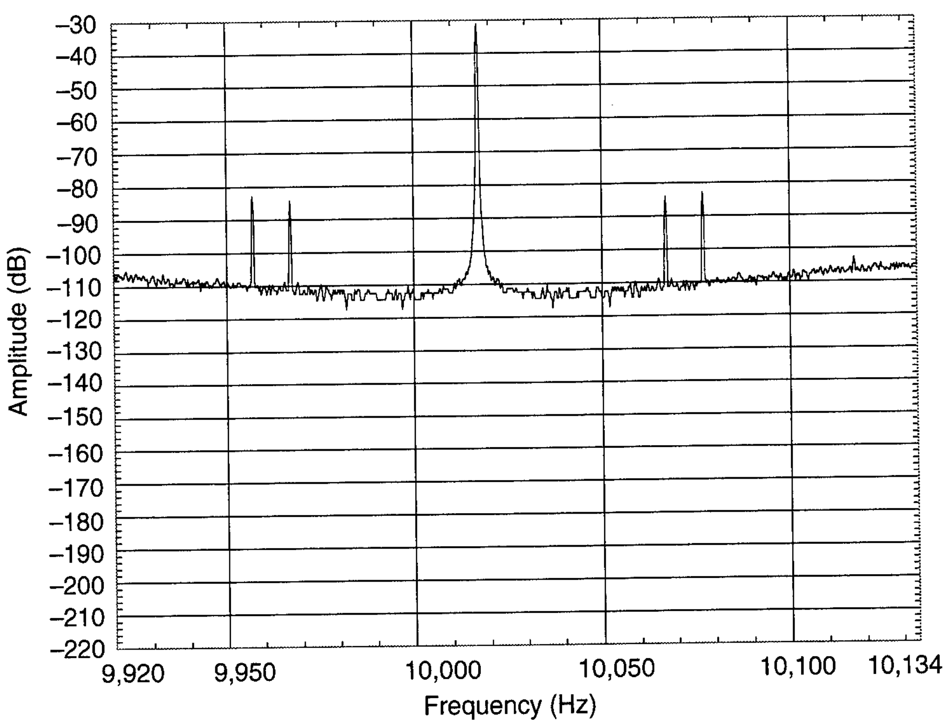


Figure C-121. Oscillator 74, 31.9 g at 50 Hz, screw sideways, vertical vibration, $\gamma = 1.62 \times 10^{-9}/g$.

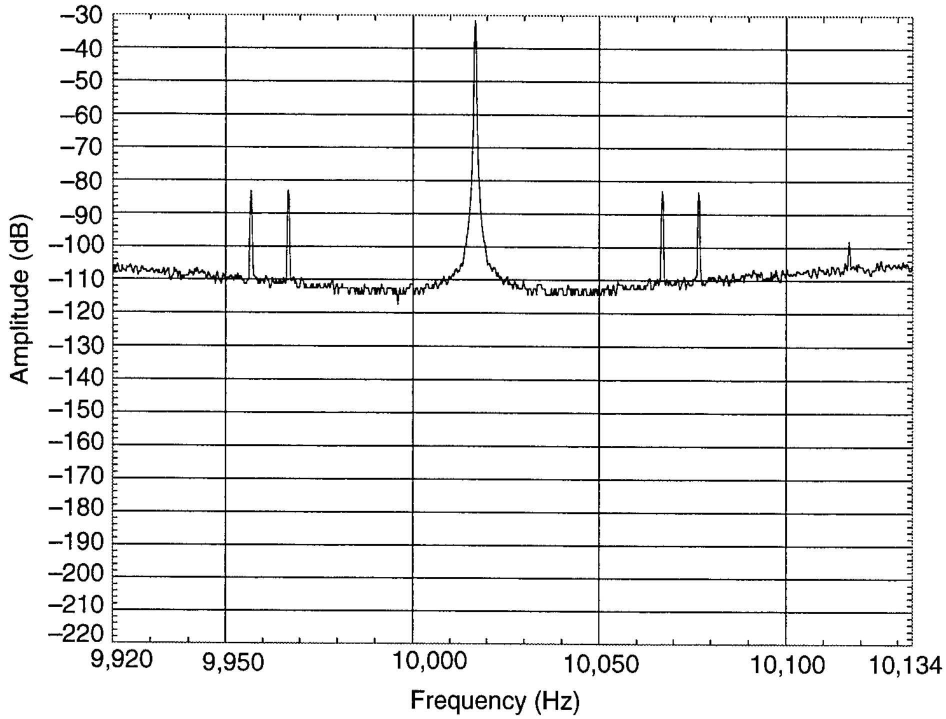


Figure C-122. Oscillator 74, 1 g at 500 Hz, screw sideways, vertical vibration, No Signal.

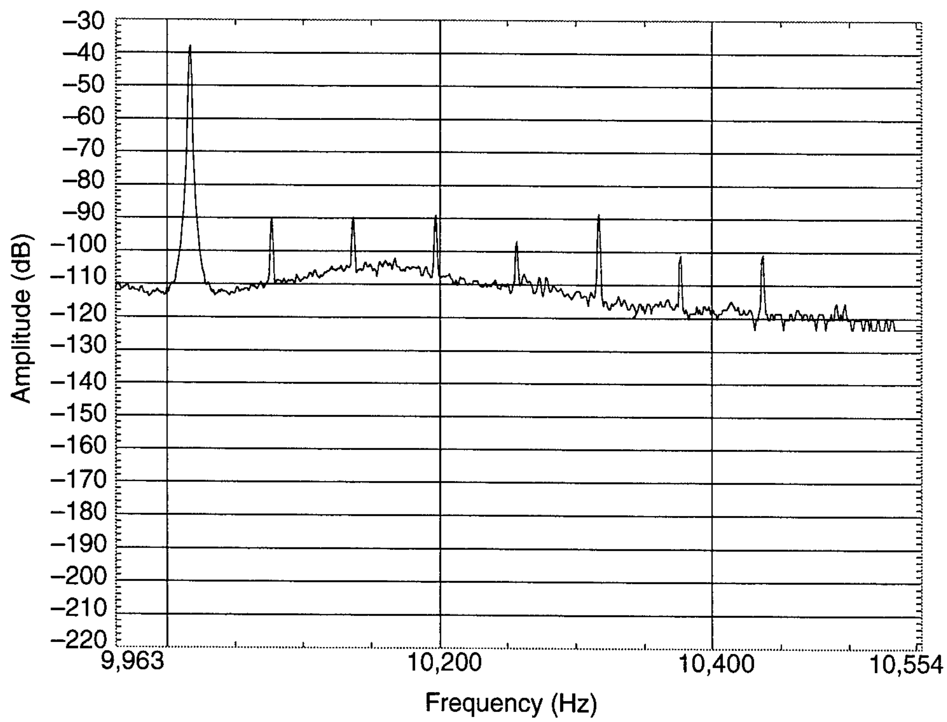


Figure C-123. Oscillator 74, 5 g at 500 Hz, screw sideways, vertical vibration, $\gamma = 2.24 \times 10^{-9}/g$.

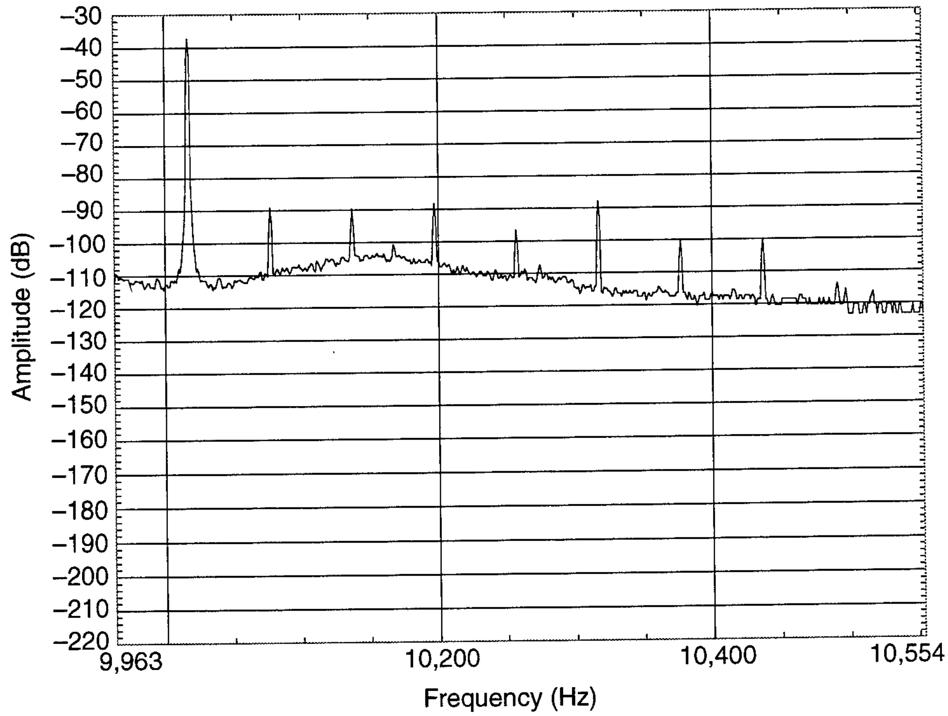


Figure C-124. Oscillator 74, 10 g at 500 Hz, screw sideways, vertical vibration, $\gamma = 1.12 \times 10^{-9}/g$.

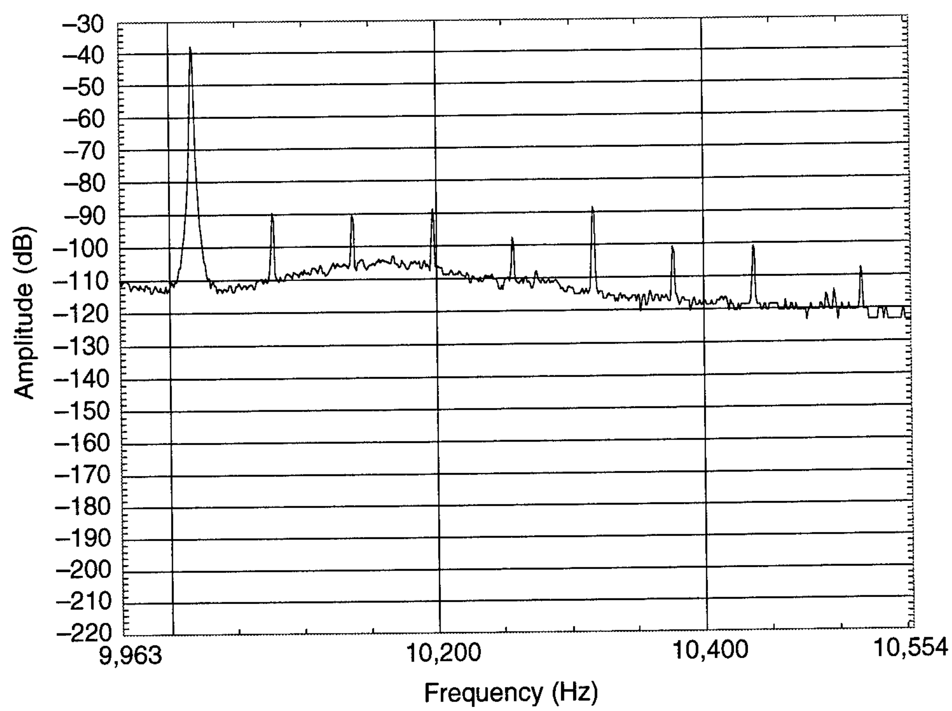


Figure C-125. Oscillator 74, 25 g at 500 Hz, screw sideways, vertical vibration, $\gamma = 4.50 \times 10^{-9}/g$.

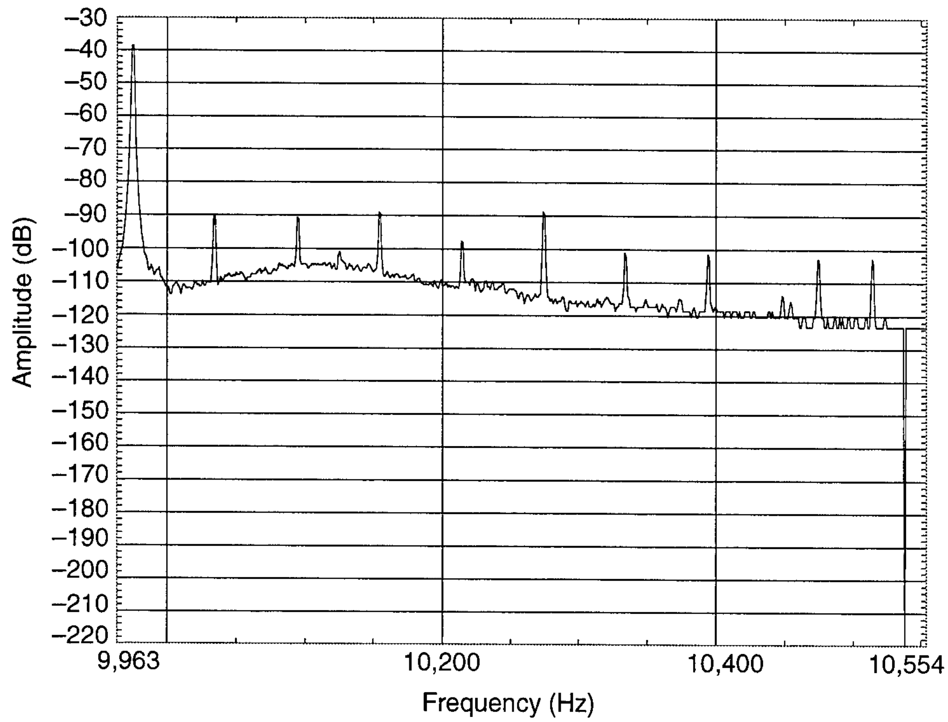
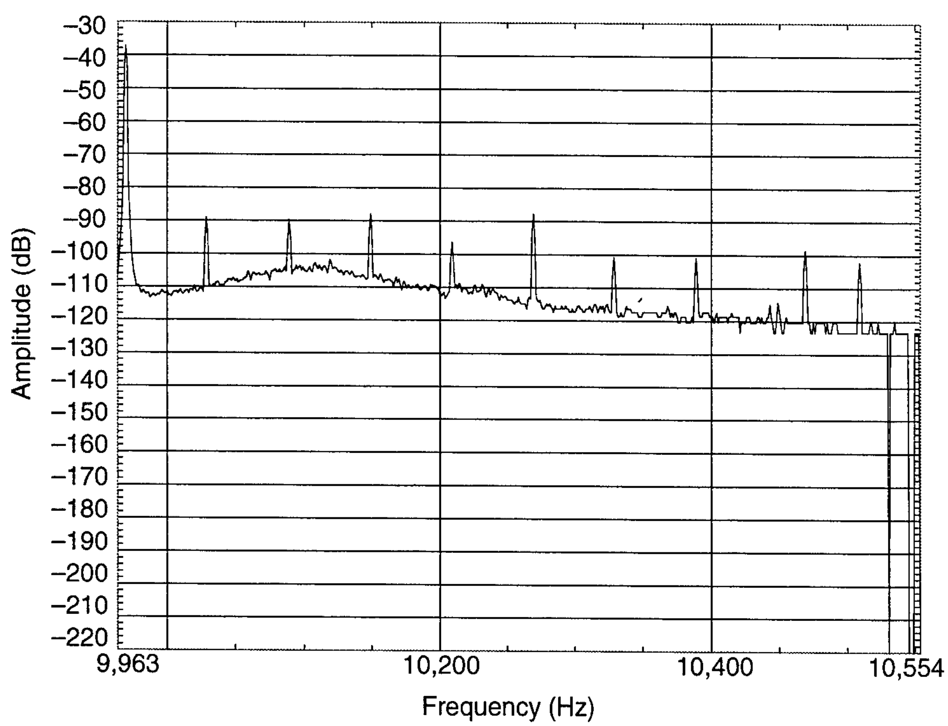


Figure C-126. Oscillator 74, 40 g at 500 Hz, screw sideways, vertical vibration, $\gamma = 4.46 \times 10^{-9}/g$.



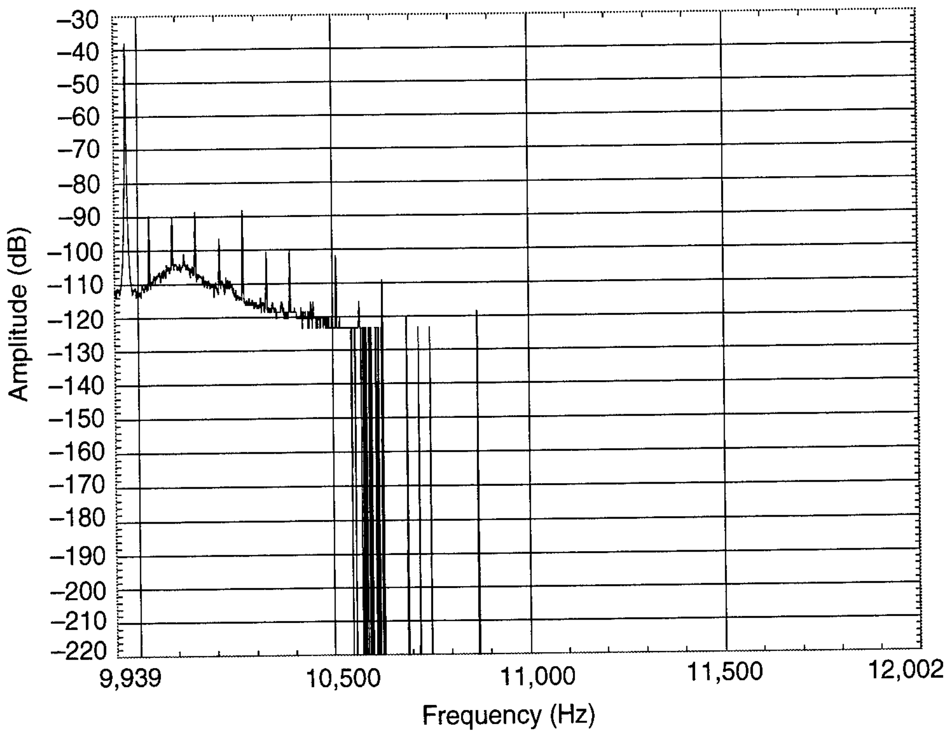


Figure C-127. Oscillator 74, 1 g at 1000 Hz, screw sideways, vertical vibration, no signal.

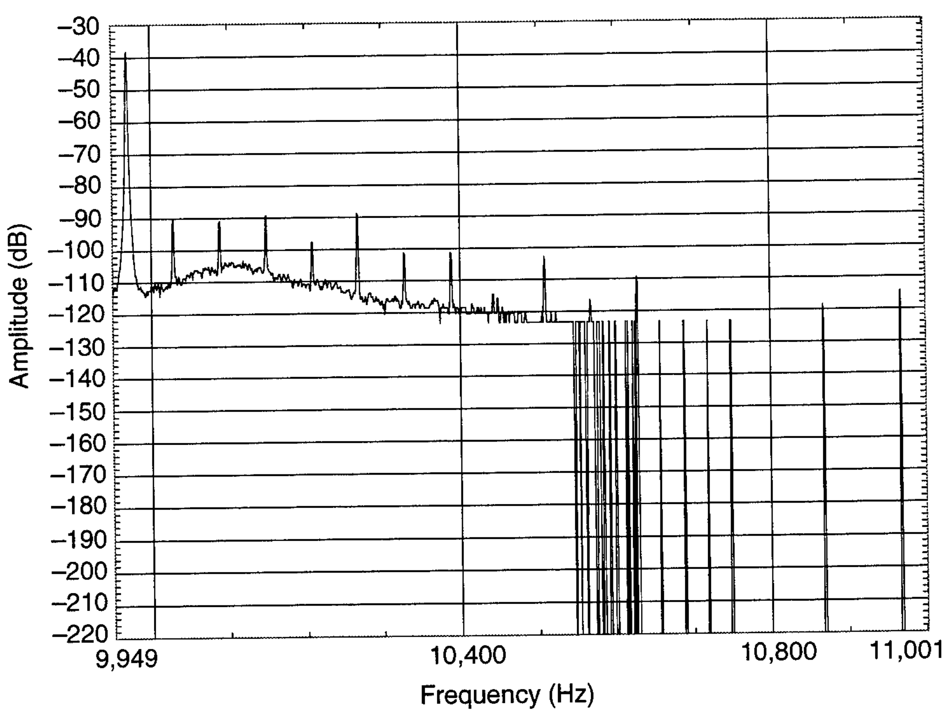


Figure C-128. Oscillator 74, 5 g at 1000 Hz, screw sideways, vertical vibration, 1.42×10^{-8}.

Figure C-129. Oscillator 74, 10 g at 1000 Hz, screw sideways, vertical vibration, $\gamma = 7.98 \times 10^{-9}$/g.

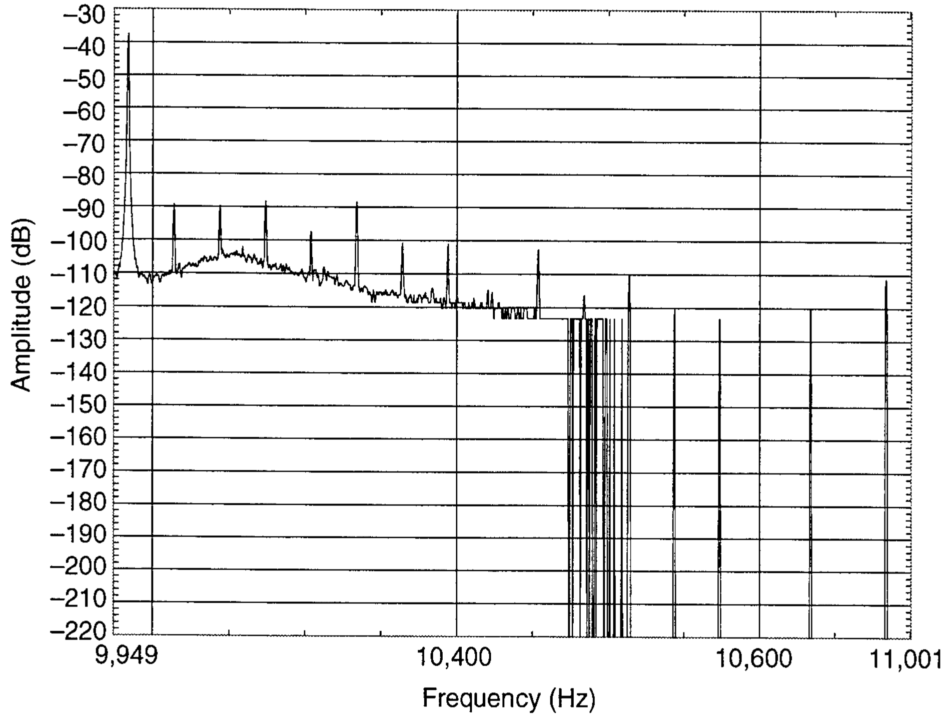


Figure C-130. Oscillator 74, 25 g at 1000 Hz, screw sideways, vertical vibration, $\gamma = 4.02 \times 10^{-8}$/g.

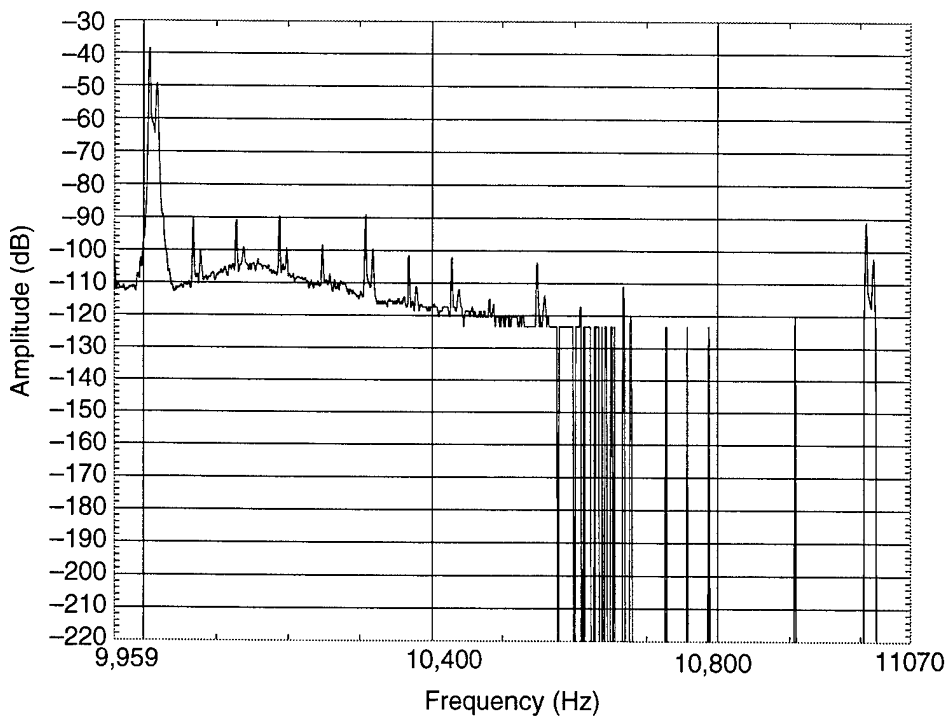
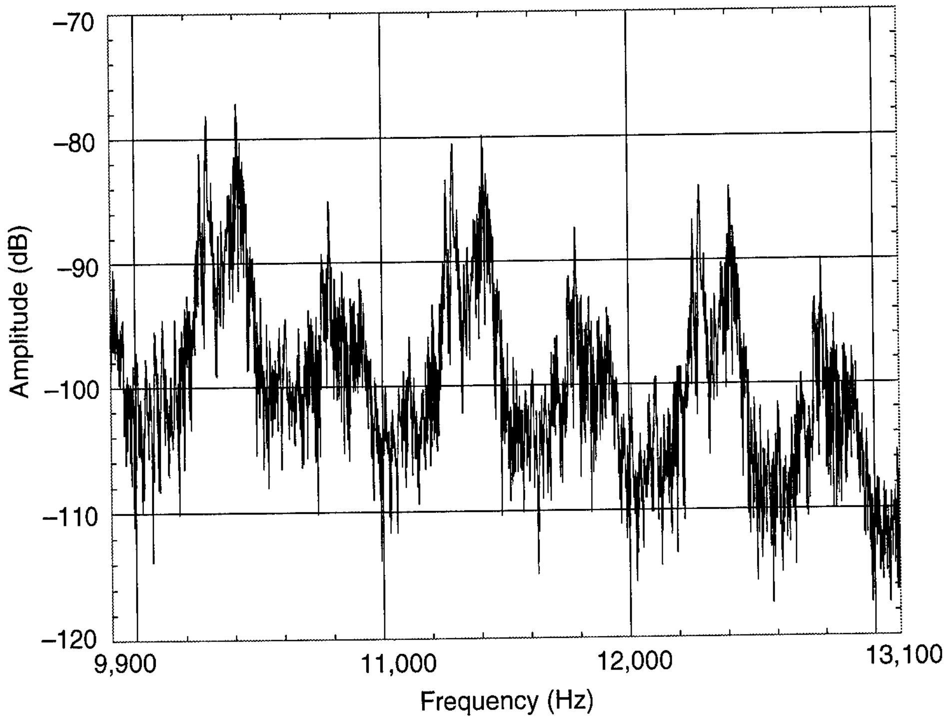


Figure C-131. Oscillator 74, 40 g at 1000 Hz, screw sideways, vertical vibration, crystal no longer working.



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13. ABSTRACT *(Maximum 200 words)*

The U.S. Army Research Laboratory (ARL), specifically the RF Electronics Division of the Sensors and Electron Devices Directorate, has been tasked to become the Department of Defense (DoD) center for frequency control. As part of this program, ARL and others will develop frequency oscillators to be used as system clocks in munitions and other devices. ARL has assembled a test facility to measure the effects of vibration on frequency oscillators. This report discusses the results of vibration experiments on two quartz crystal oscillators, including verification of the measurement system and experimental setup.

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